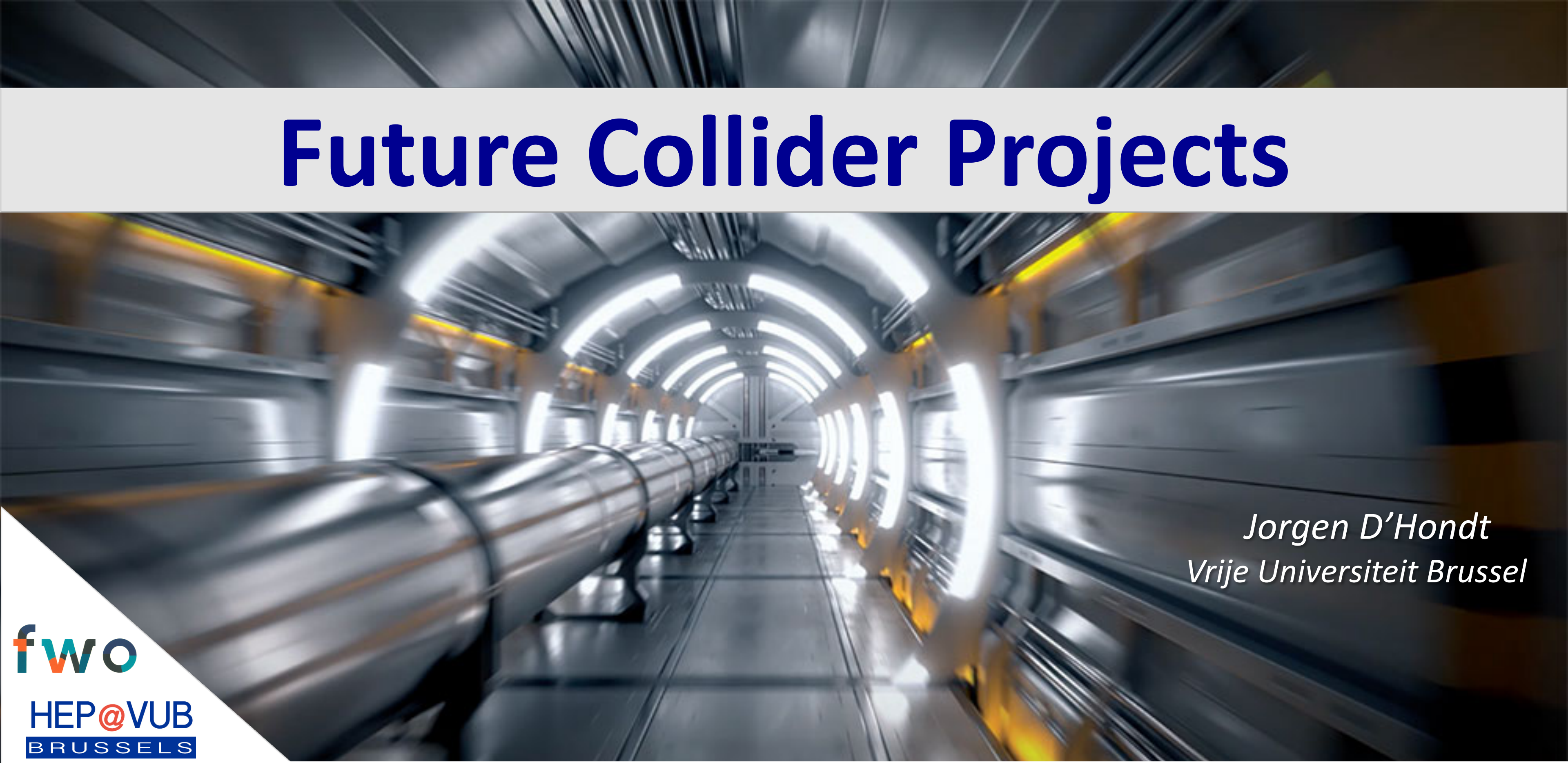
Future Collider Projects



Jorgen D'Hondt
Vrije Universiteit Brussel

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HEP@VUB BRUSSELS

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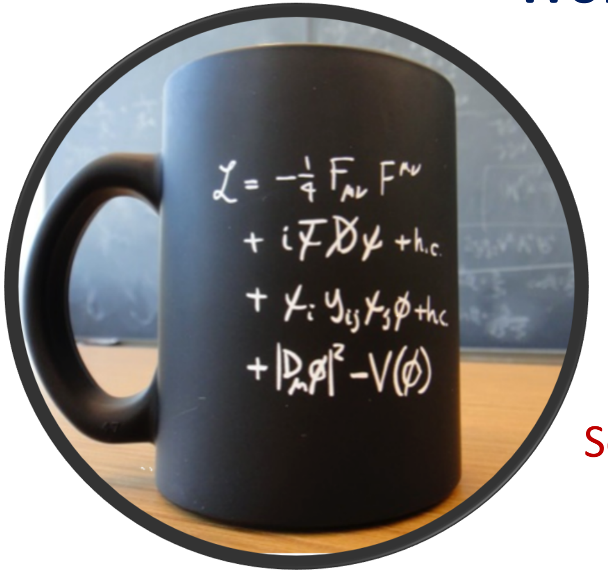
ICHEP 2020 | PRAGUE

The quest for understanding particle physics

Picture from Flip Tanedo @ Quantum Dairies



Wonderful description of fundamental interactions

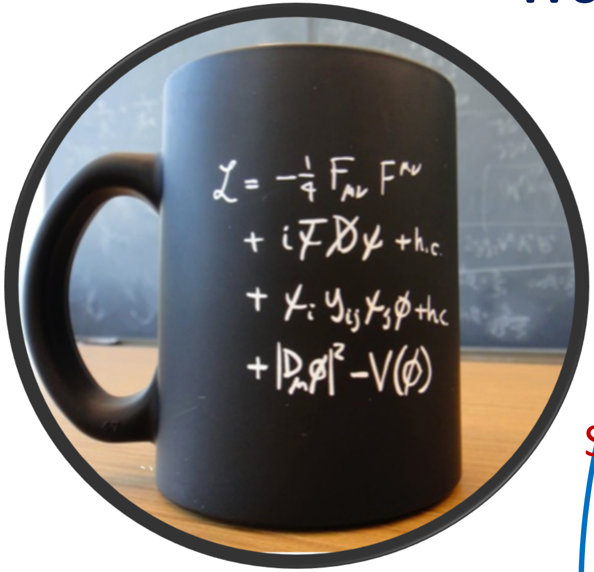
e.g. The Standard Models of Particle Physics and Cosmology
together do not describe all our observations of the universe.

"Problems and Mysteries"

[Riccardo Rattazzi]

e.g. Abundance of dark matter?
Abundance of matter over antimatter?
Scale of things (EW hierarchy problem / strong CP problem)?
Pattern of fermion masses and mixings?
Dynamics of EW symmetry breaking?...

The quest for understanding particle physics



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Important research in ph & th relates these to a portfolio of concrete observable phenomena at colliders and elsewhere

In many cases synergies emerge between astro(particle), cosmology, nuclear and particle physics

The quest for understanding particle physics

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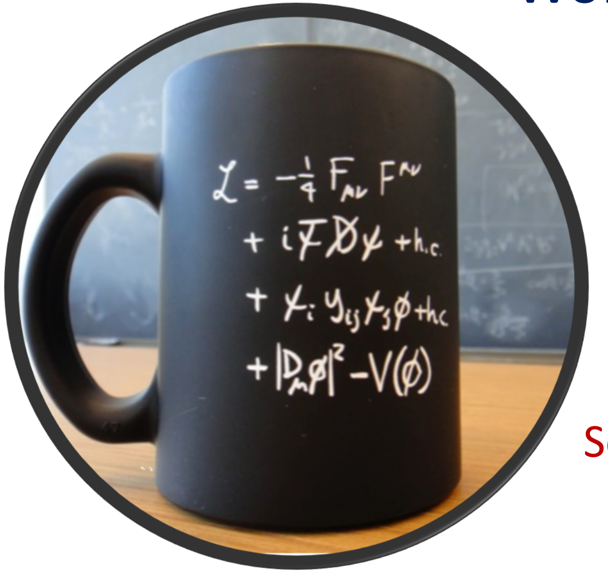

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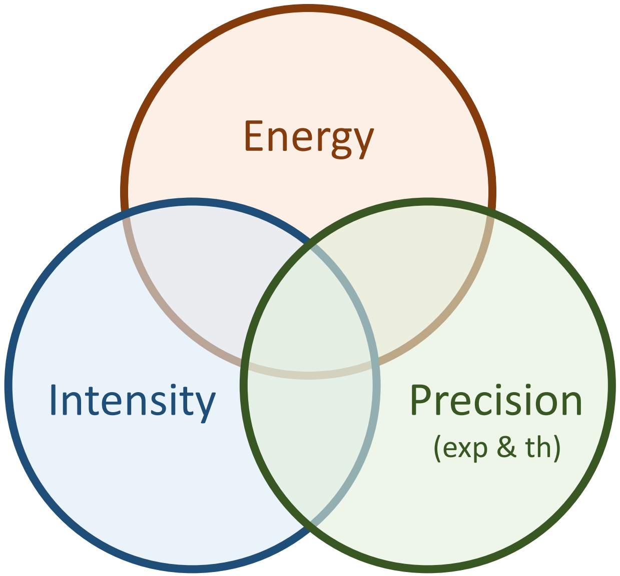
Observations of new physics phenomena are expected to unlock concrete ways to address these puzzling unknowns

Three frontiers on the collider route to BSM



- Accelerator R&D – Vladimir Shiltsev
- Detector R&D – Paula Collins
- Computing and Software – James Catmore
- Theory – Fabio Maltoni & Eric Kuflik

Extending these collider frontiers remains our prime route to those BSM phenomena related to the most important open questions

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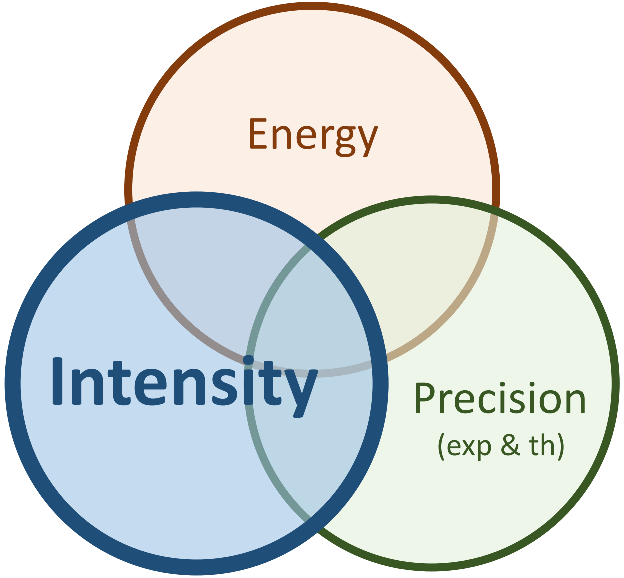

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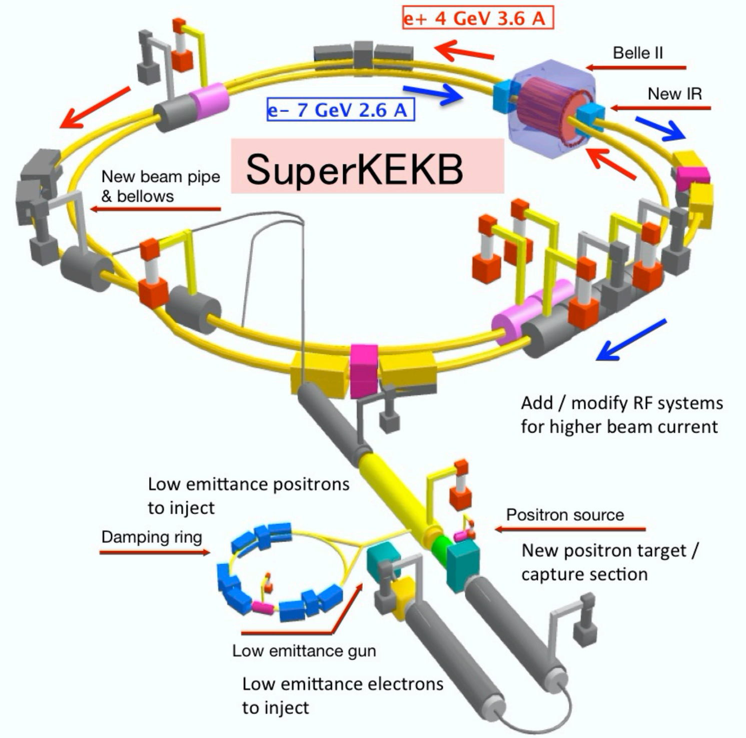
Congratulations to SuperKEKB!

e^+e^- collider at the Υ(4S)≈10.5GeV
B-Factory for the Belle II experiment

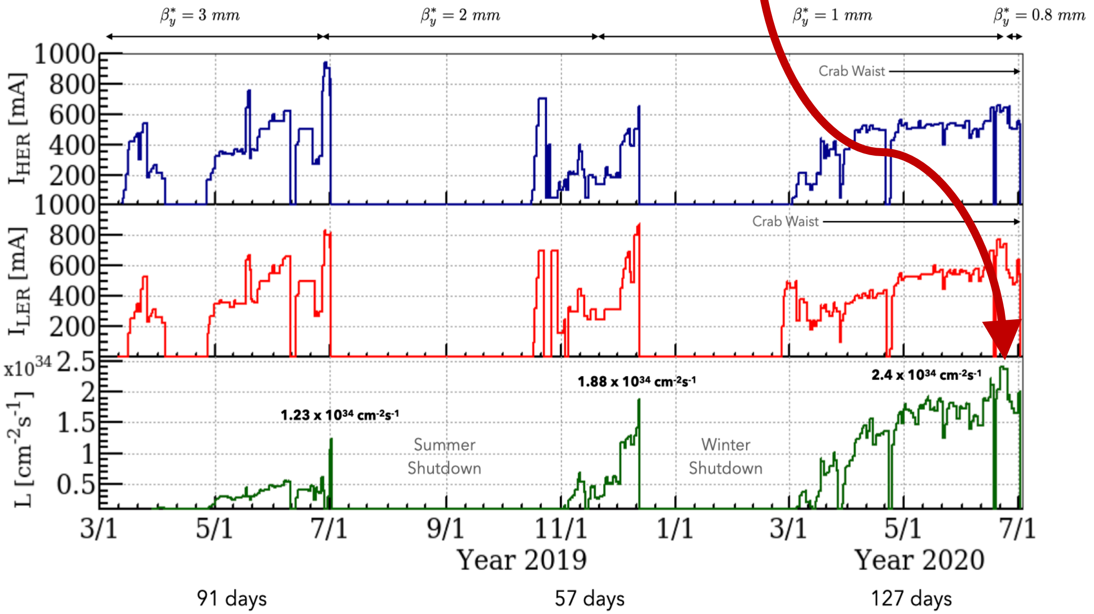
world record luminosity

2.4 10^{34} $cm^{-2}s^{-1}$ (June 2020)
(ultimate target 8 10^{35} $cm^{-2}s^{-1}$)

1st ever nano-beam scheme



Y. Ohnishi



Note: SuperKEKB takes over the luminosity record from the LHC

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...no-beam scheme

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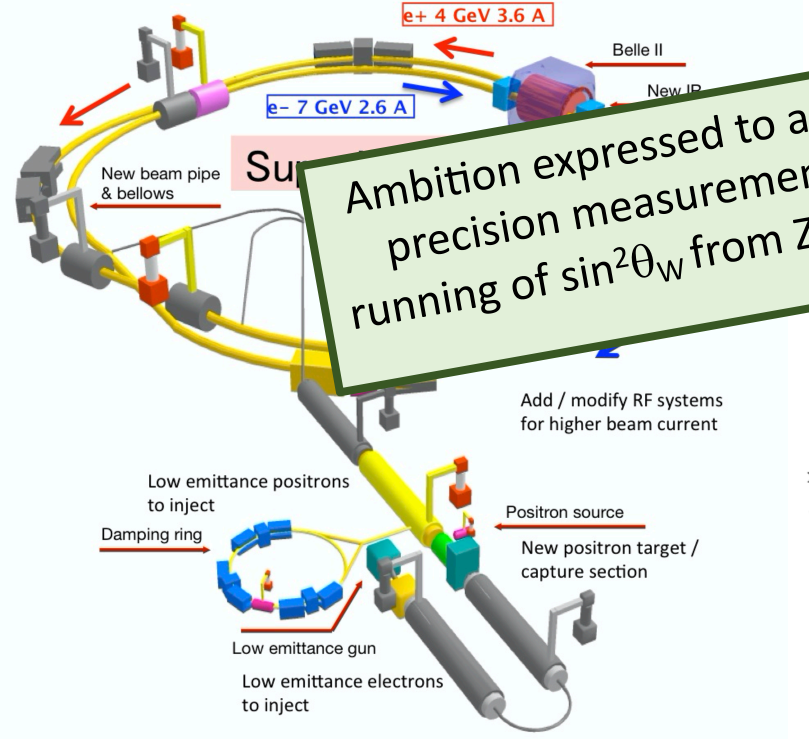
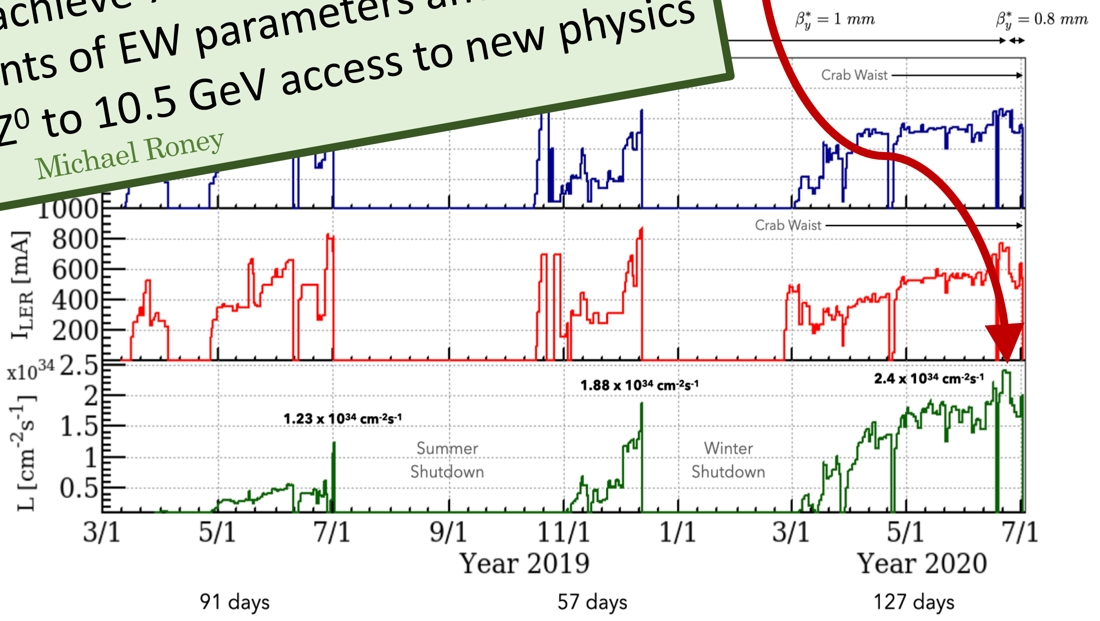


Ambition expressed to achieve 70% polarized e^- beams for precision measurements of EW parameters and via the running of $\sin^2\theta_W$ from Z^0 to 10.5 GeV access to new physics

Michael Roney



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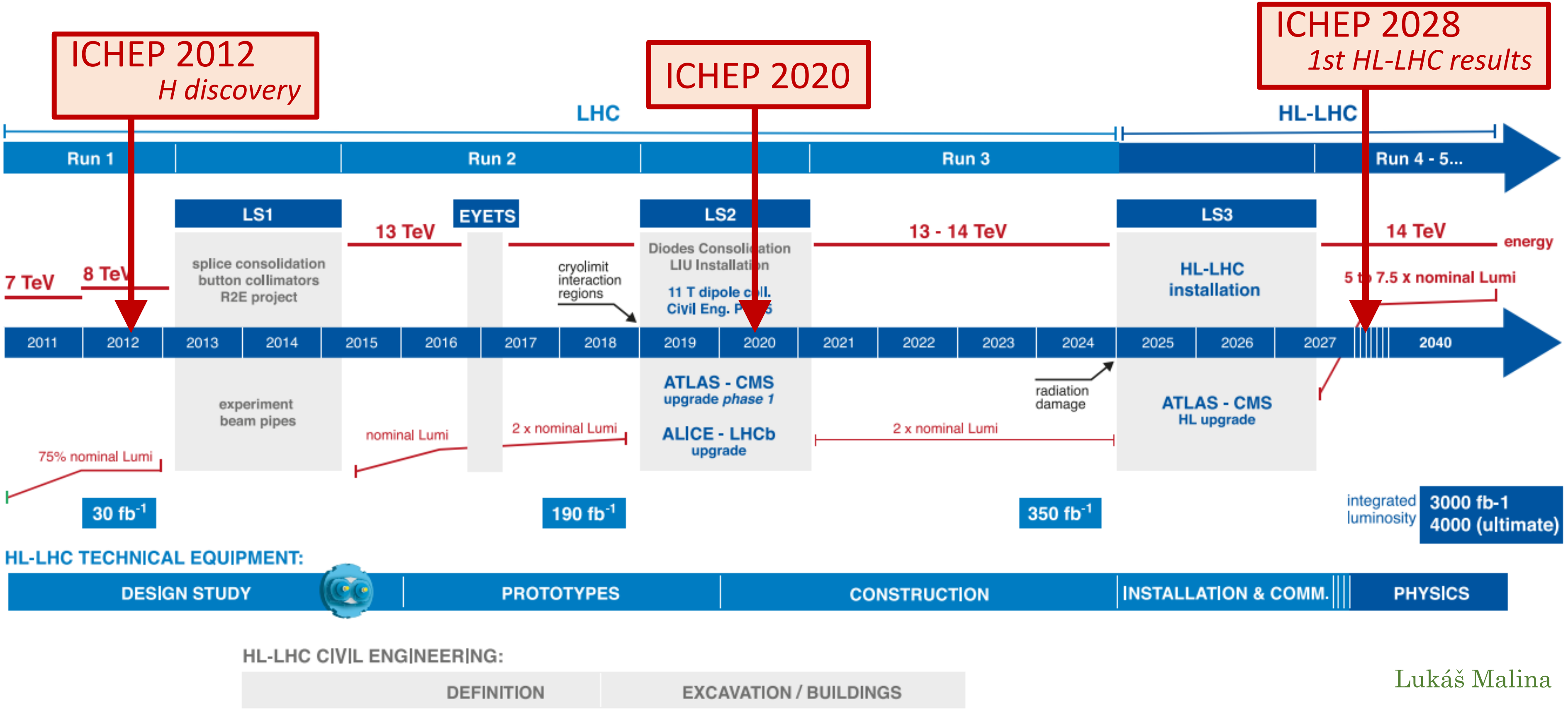
From the LHC to the High-Luminosity LHC @ CERN



From the LHC to the High-Luminosity LHC @ CERN

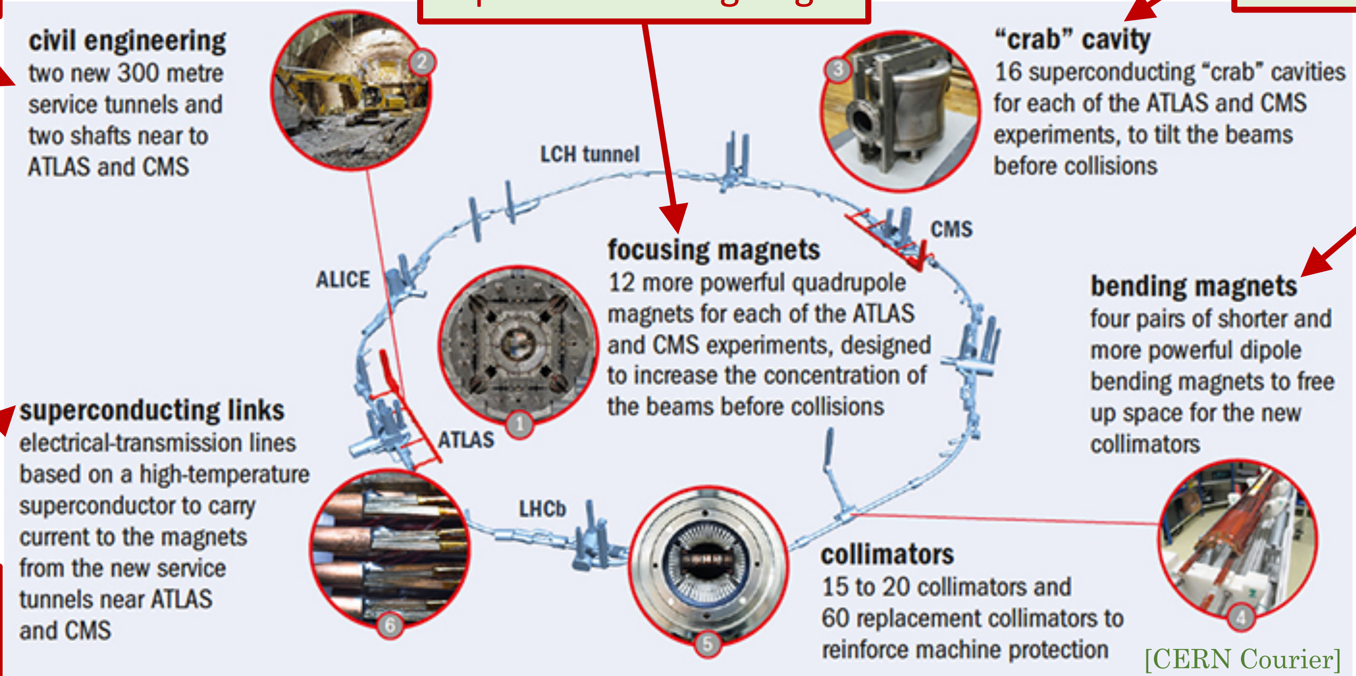
excavation mostly done

successfully tested (US) production ongoing

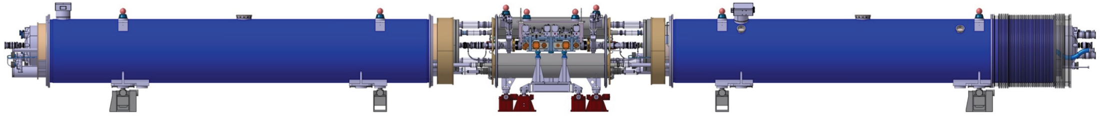
successfully tested at SPS (CERN)

ongoing tests on bench, some qualified (CERN)

60m system demonstrator successful (CERN)



[CERN Courier]



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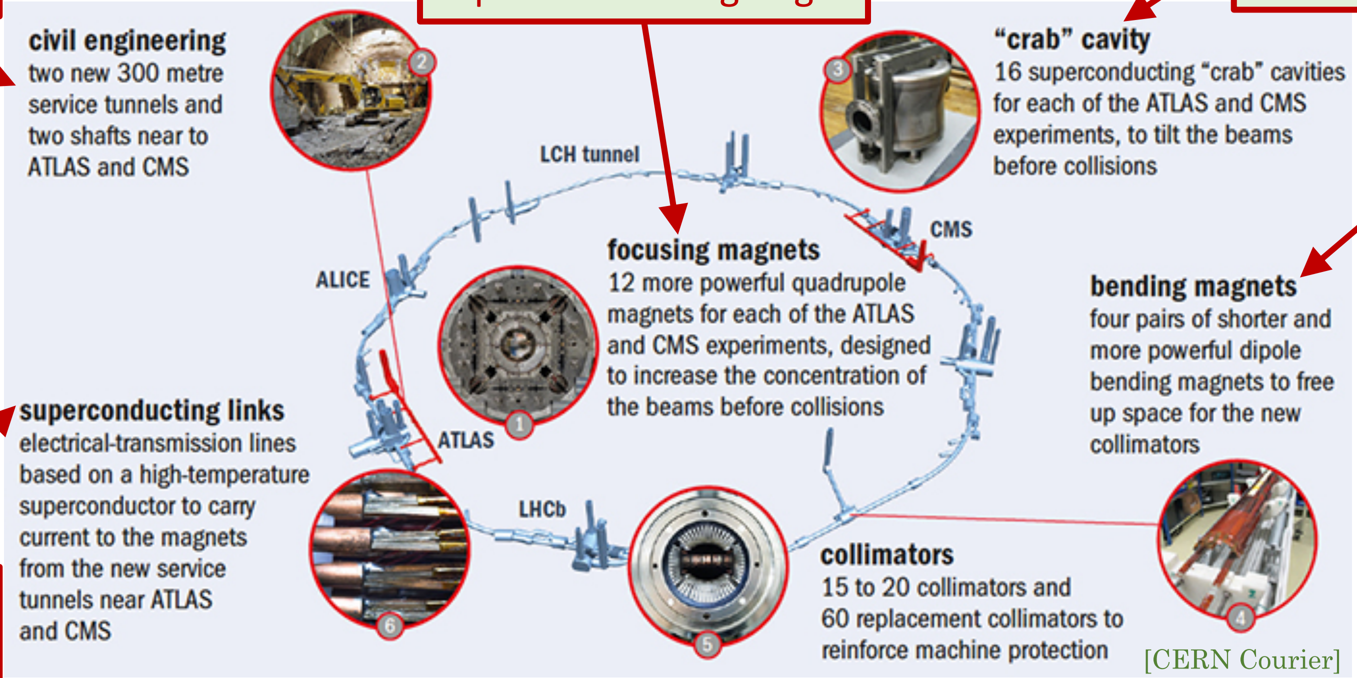
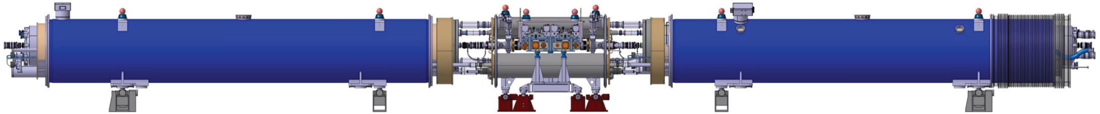
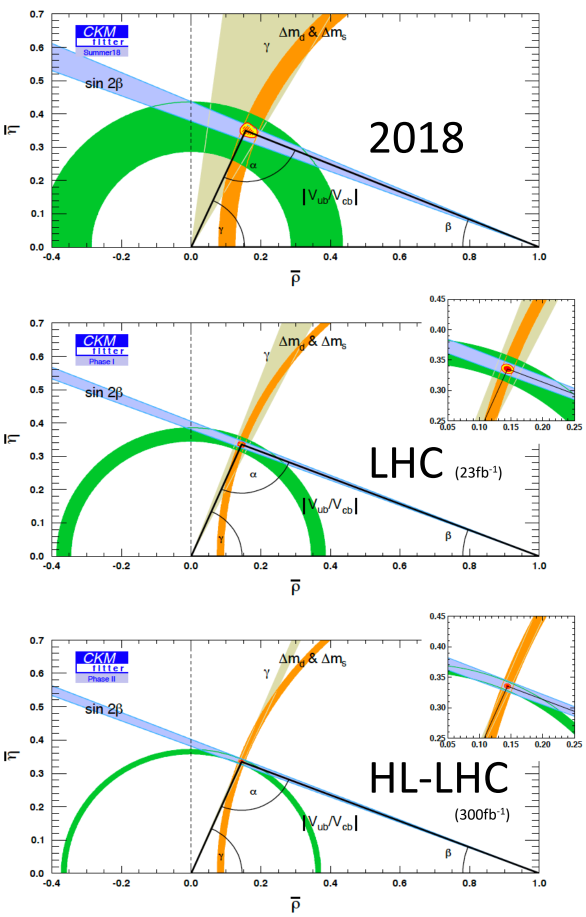


60m system demonstrator successful (CERN)



From the LHC to the High-Luminosity LHC @ CERN

[Physics case for an LHCb Upgrade II, https://arxiv.org/pdf/1808.08865.pdf]



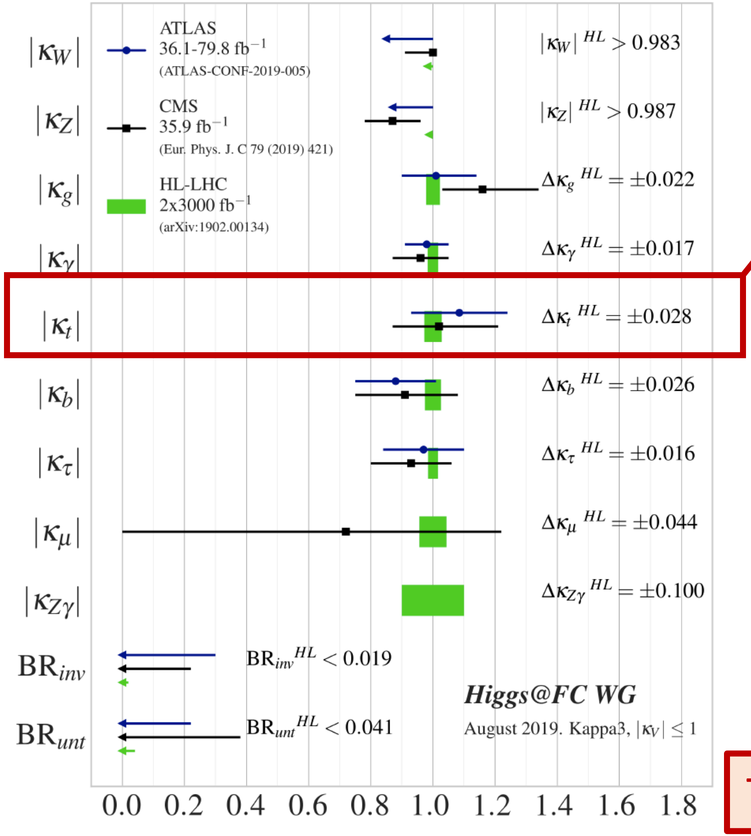
- Constraining the parameters of the unitary CKM matrix (not predicted by the SM) will provide an extremely precise test of the paradigm, and through loop corrections a powerful sensitivity to BSM physics *(figure from LHCb only)*
- Expected improvement from LHC and Belle II *(table)*

	λ	$\bar{\rho}$	$\bar{\eta}$	A	$\sin 2\beta$	γ	α	β_s
Current	0.12%	9%	3%	1.5%	4.5%	3%	2.5%	3%
short-term	0.12%	2%	0.8%	0.6%	0.9%	0.9%	0.7%	0.8%
mid-term	0.12%	1%	0.6%	0.5%	0.6%	0.8%	0.4%	0.5%

[arXiv:1812.07638v2]

- In general, not limited by experimental or theoretical systematic uncertainties
- Sensitivity to BSM up to 10^3-10^6 TeV assuming $\mathcal{O}(1)$ coupling strength, depending on flavour
- Addressing significantly the flavour puzzle question

From the LHC to the High-Luminosity LHC @ CERN



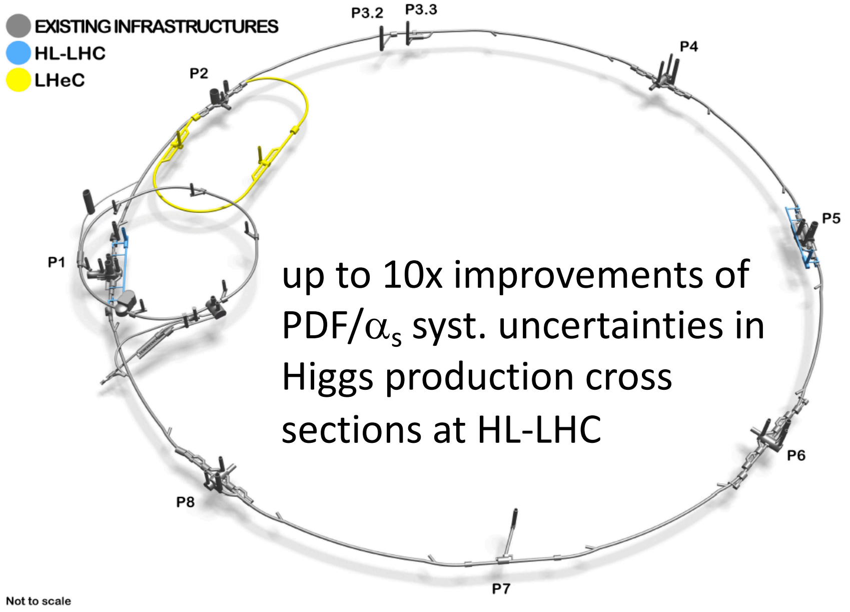
[Physics Briefing Book, http://cds.cern.ch/record/2691414]

- The Higgs couplings are expected to improve significantly with the HL-LHC data
- The estimate made in 2013 for κ_t was a precision of 7-10% with 3000fb^{-1}, while now a value better than 4% seems reachable (for the same integrated luminosity)
- With only 6 years of experimental and theoretical innovations a factor of 2 improvement, and yet 20 years to go into the research program
- Recent innovations in instrumentation, software, computing, analysis and theoretical reasoning unlocked several new avenues for research that were previously thought unreachable…

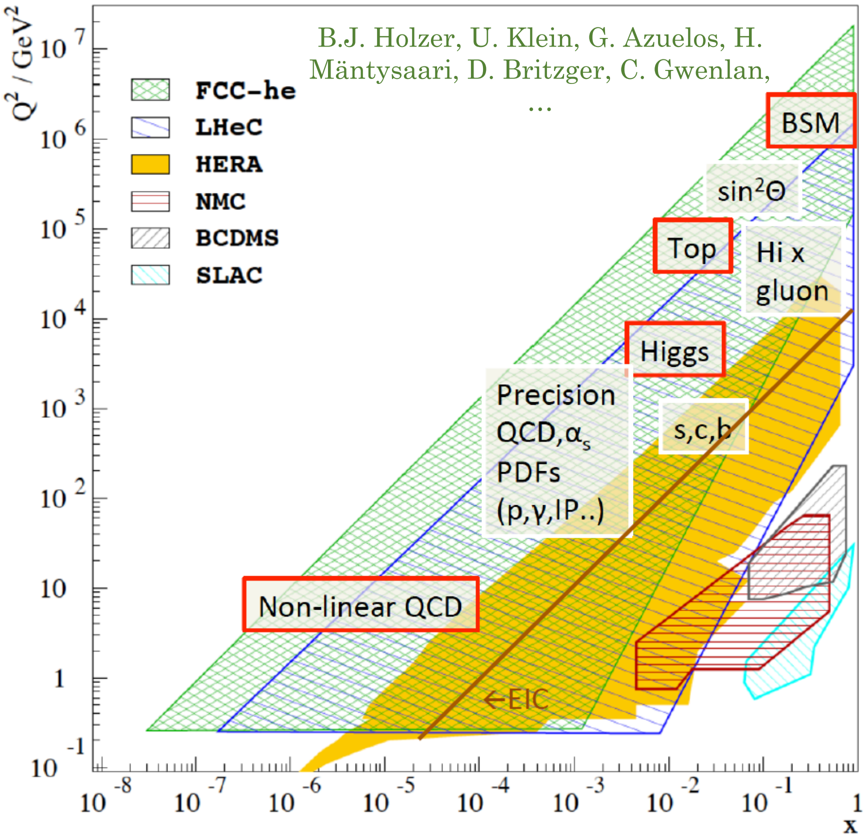
The HL-LHC is an outstanding platform for innovations!

Empowering the HL-LHC program with the LHeC

LHeC (up to 60 GeV e^- from Energy Recovery Linac)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run with the HL-LHC (≳ Run5)
ERL R&D demonstrator at Orsay, PERLE



up to 10x improvements of PDF/α_s syst. uncertainties in Higgs production cross sections at HL-LHC



[updated CDR submitted: https://arxiv.org/abs/2007.14491]

Electron-Ion Collider (EIC)

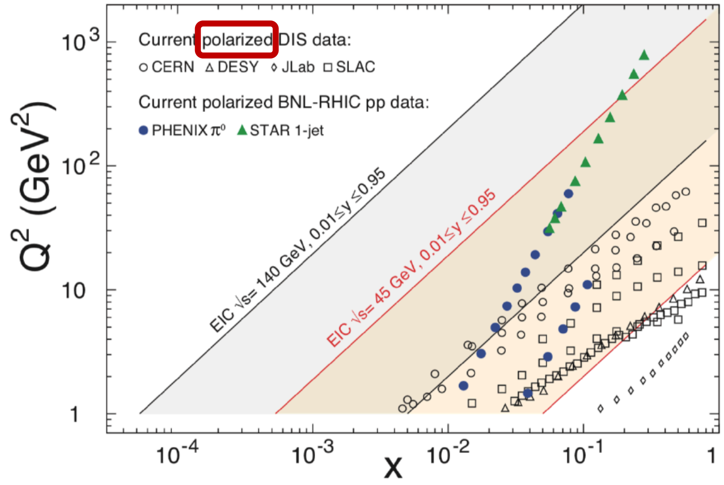
World's 1st polarized e-p/light-ion & 1st eA collider

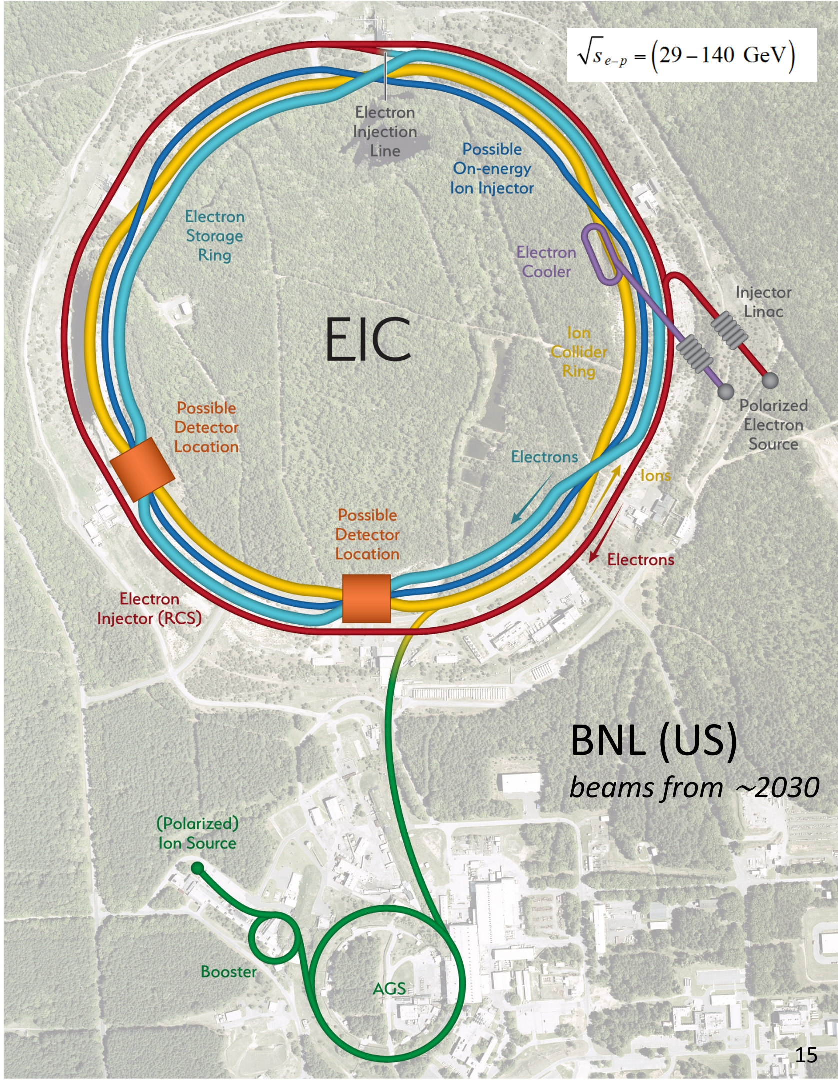
User Group >1000 members: http://eicug.org

The EIC can address three key questions.

- *How does the mass of the nucleon arise?*
- *How does the spin of the nucleon arise?*
- *What are the emergent properties of a dense system of gluons?*

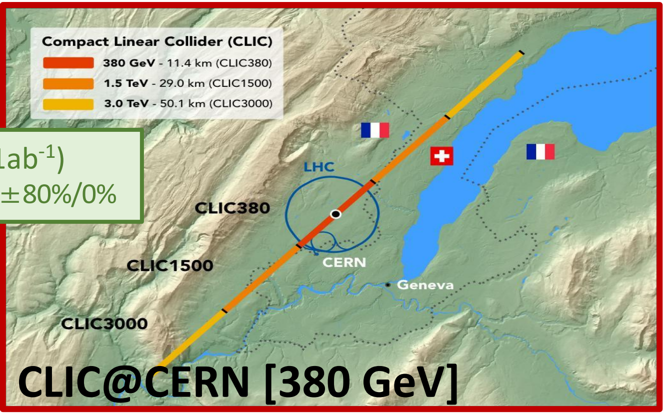
Towards a 3D partonic image of the proton (spin-dependent transverse momentum distributions)





e^+e^- Higgs Factories

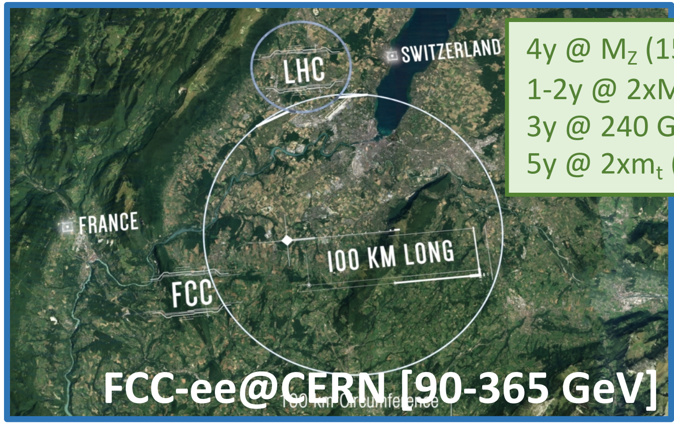
P. Burrows, M. Weber, P. Roloff, …



8 years ($1ab^{-1}$)
$\mathcal{P}(e^-/e^+) = \pm 80\%/0\%$

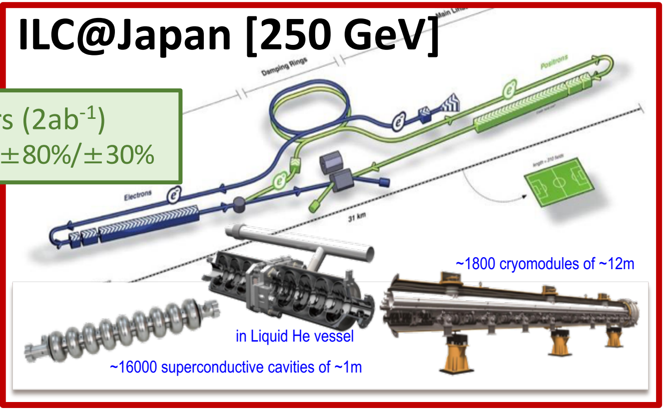
linear colliders

D. d'Enterria, A. Blondel, P. Janot, …



4y @ M_Z ($150ab^{-1}$)
1-2y @ $2xM_W$ ($10ab^{-1}$)
3y @ 240 GeV ($5ab^{-1}$)
5y @ $2xm_t$ ($1.5ab^{-1}$)

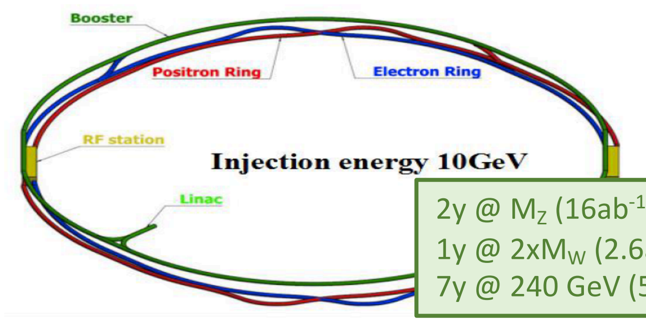
circular colliders



11.5 years ($2ab^{-1}$)
$\mathcal{P}(e^-/e^+) = \pm 80\%/\pm 30\%$

J. List, M. Peskin, D. Jeans, G. Wilson, T. Nuñez, …

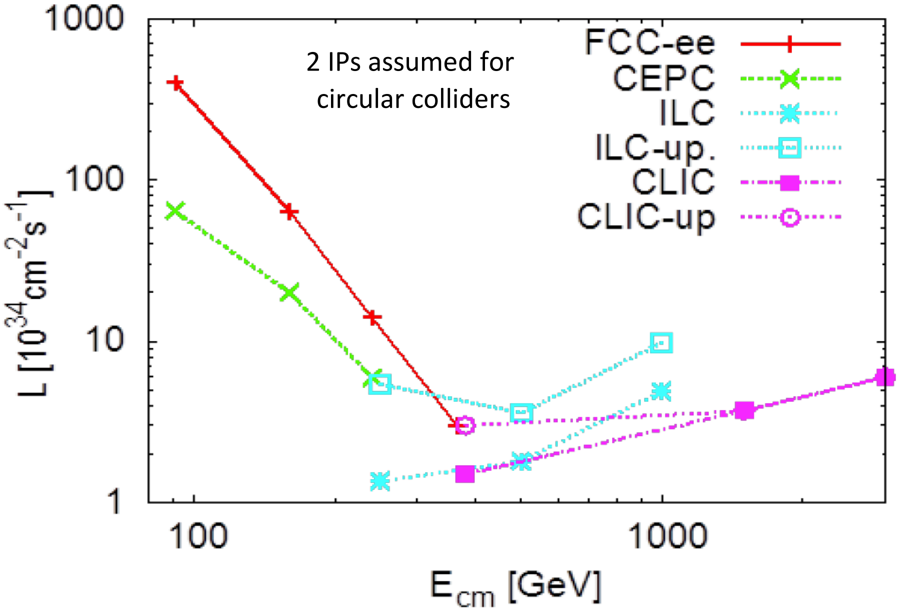
CEPC@China [90-240-(350) GeV]



2y @ M_Z ($16ab^{-1}$)
1y @ $2xM_W$ ($2.6ab^{-1}$)
7y @ 240 GeV ($5.6ab^{-1}$)

J. Gao, M. Pandurovic, …

e^+e^- Higgs Factories



e^+e^- Higgs Factories

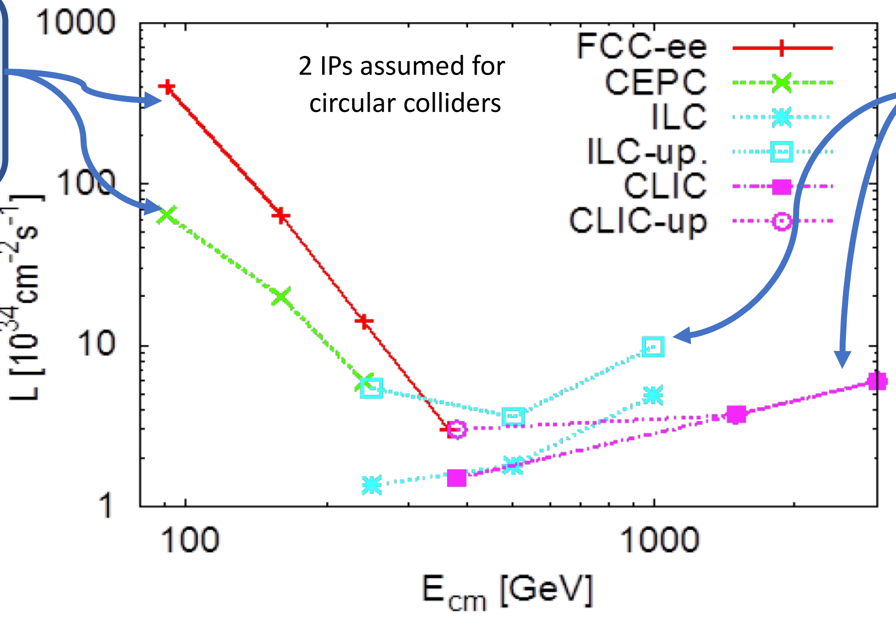
precision frontier

circular colliders

synchrotron radiation

for the same power, less luminosity at higher E_{cm}

(Energy Recovery Linac technology might mitigate this & allow to go to higher E_{cm})



linear colliders

energy frontier

e^+e^- Higgs Factories

precision frontier

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synchrotron radiation

↓

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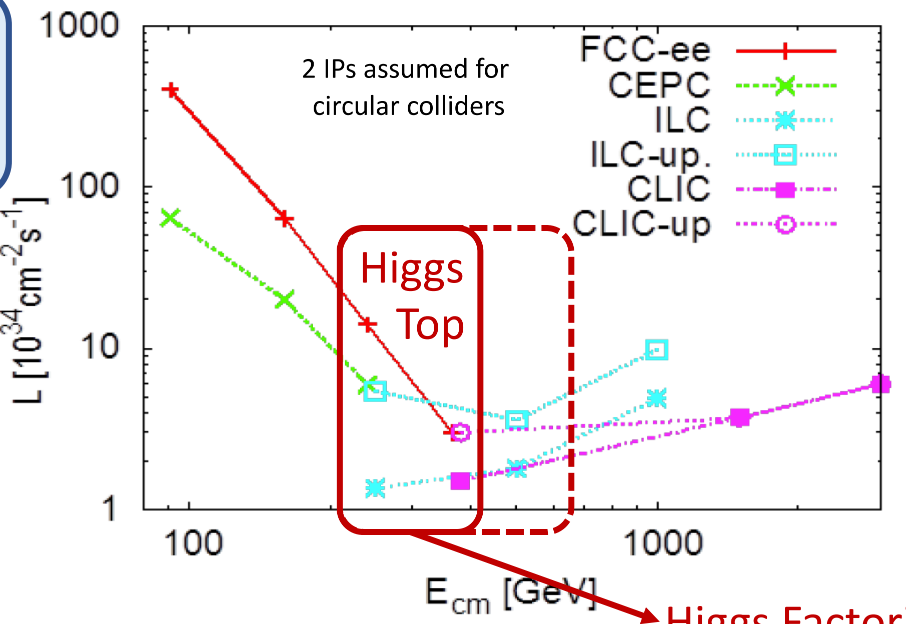

linear colliders

energy frontier

Higgs Factories with complementarity

- g_{HZZ} (250GeV) versus g_{HWW} (380GeV)
- top quark physics
- beam polarization for EW precision tests

(transverse polarization in circular e^+e^- colliders only at lower E_{cm} while longitudinal polarization at linear colliders)

e^+e^- Higgs Factories

precision frontier

circular colliders

synchrotron radiation

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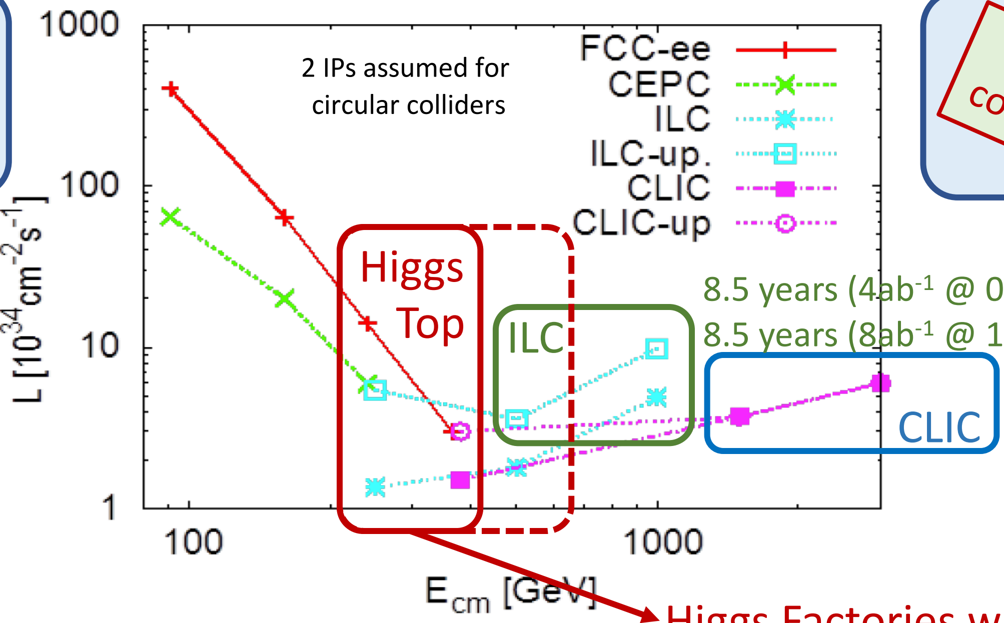

8.5 years (4ab^{-1} @ 0.5 TeV)

8.5 years (8ab^{-1} @ 1 TeV)

7 years (2.5ab^{-1} @ 1.5 TeV)

8 years (5ab^{-1} @ 3 TeV)

linear colliders

energy frontier

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e^+e^- Higgs Factories (incl. B/c/τ/EW/top factories)

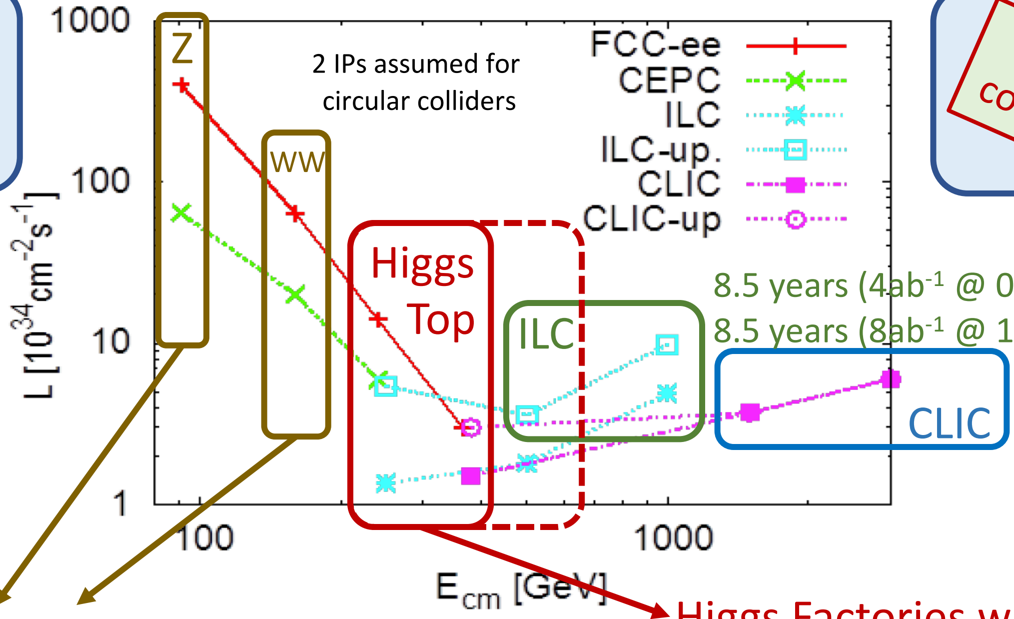
precision frontier — circular colliders

synchrotron radiation

↓

for the same power, less luminosity at higher E_{cm}

(Energy Recovery Linac technology might mitigate this & allow to go to higher E_{cm})



linear colliders — energy frontier

8.5 years ($4ab^{-1}$ @ 0.5 TeV)

8.5 years ($8ab^{-1}$ @ 1 TeV)

7 years ($2.5ab^{-1}$ @ 1.5 TeV)

8 years ($5ab^{-1}$ @ 3 TeV)

B/c/τ/EW Factories

per detector in e^+e^-	# Z	# B	# τ	# charm	# WW
LEP	4 x 10^6	1 x 10^6	3 x 10^5	1 x 10^6	2 x 10^4
SuperKEKB	-	10^{11}	10^{11}	10^{11}	-
FCC-ee	2.5 x 10^{12}	7.5 x 10^{11}	2 x 10^{11}	6 x 10^{11}	1.5 x 10^8

Higgs Factories with complementarity

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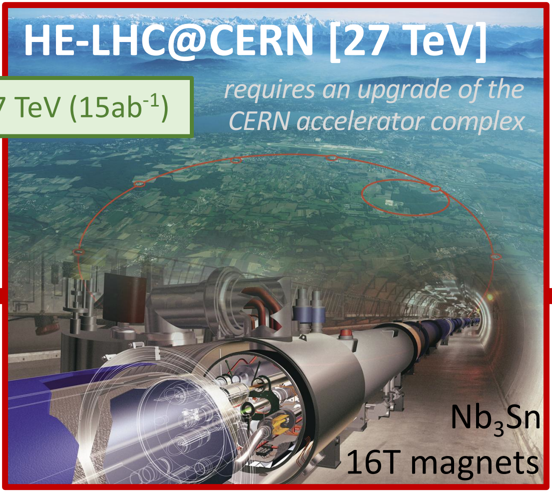
(transverse polarization in circular e^+e^- colliders only at lower E_{cm} while longitudinal polarization at linear colliders)

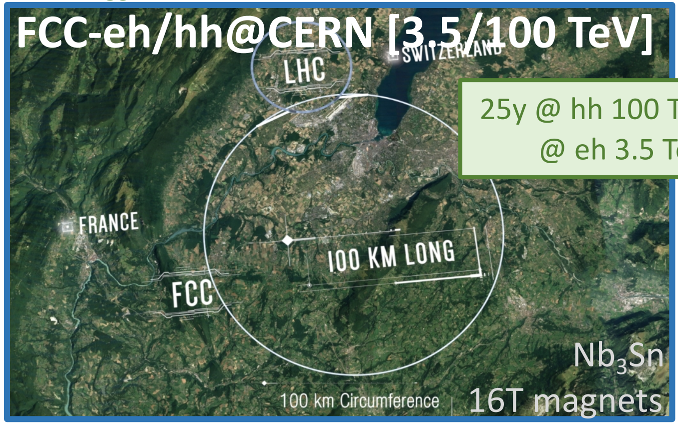
Energy frontier colliders – Hadron Colliders

Direct BSM searches at the highest energies
e.g. addressing the naturalness puzzle

20y @ 27 TeV ($15ab^{-1}$)

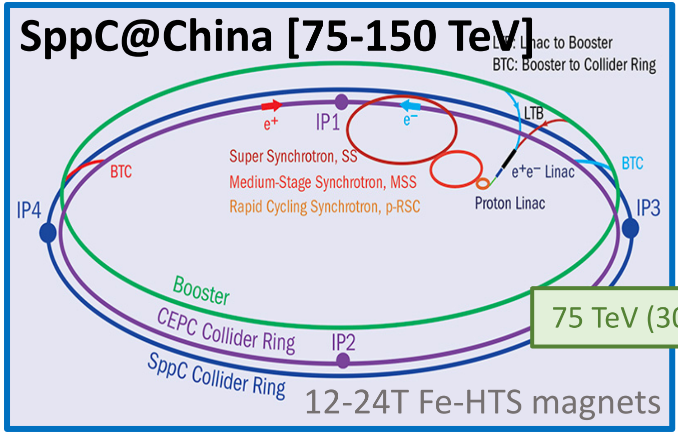


M. Selvaggi, …



25y @ hh 100 TeV ($30ab^{-1}$)
@ eh 3.5 TeV ($2ab^{-1}$)

E



75 TeV ($30ab^{-1}$)

numbers assume 2 IPs for each collider (only one for FCC-eh)

Towards an international muon collider design study

benefits
- Suppressed synchrotron radiation wrt electrons
- Luminosity can increase linearly with energy
- For the production of heavy particle pairs 14 TeV lepton collisions are comparable to 100 TeV proton collisions

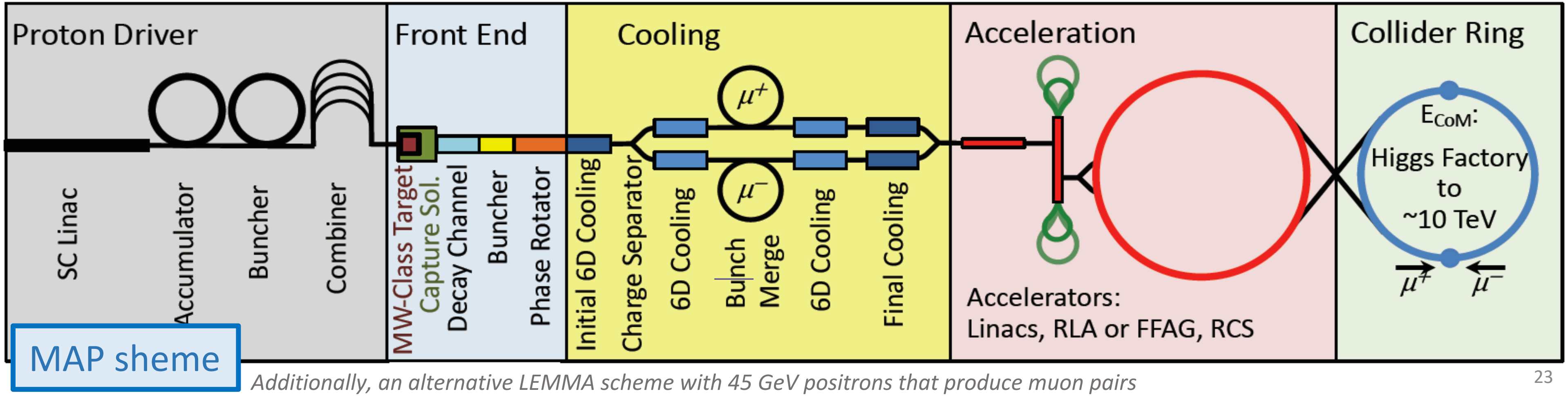
international collaboration being formed towards
a design study for a 3 TeV and >10 TeV muon collider
(incl. exploring synergies with Higgs Factories & neutrino experiments)

muon collider

D. Schulte
L. Sestini (Higgs), ...

main challenge: muon lifetime at rest only 2.2 μs

http://muoncollider.web.cern.ch

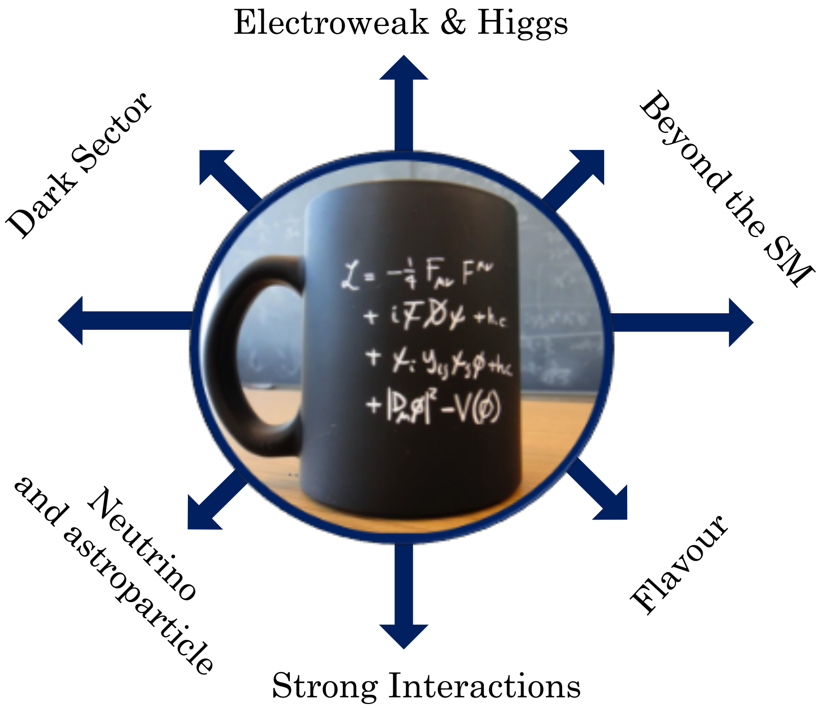


Additionally, an alternative LEMMA scheme with 45 GeV positrons that produce muon pairs

Principle collider avenues to seek new phenomena

Open questions relate to several physics phenomena that can be captures in 6 principle categories

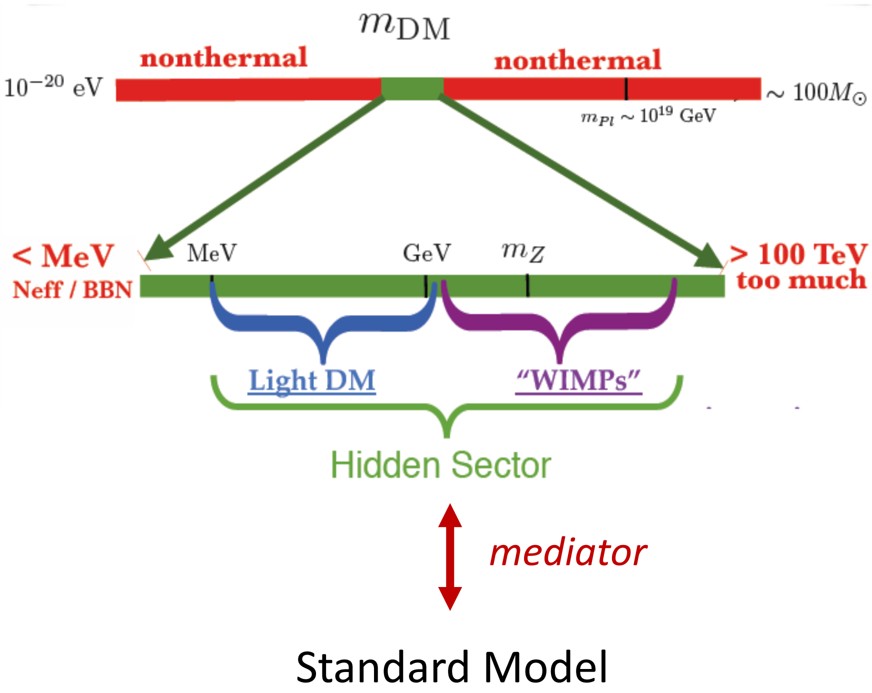
(surely other sets could be used as well)

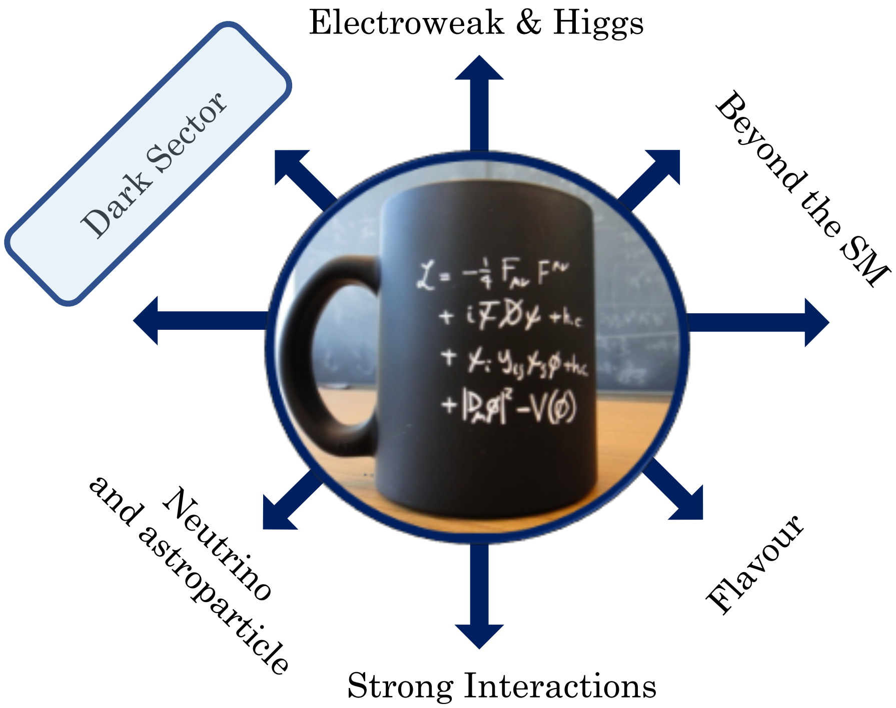


Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

Searching for dark matter with colliders

The assumption of Thermal Equilibrium in the early Universe narrows the viable mass range

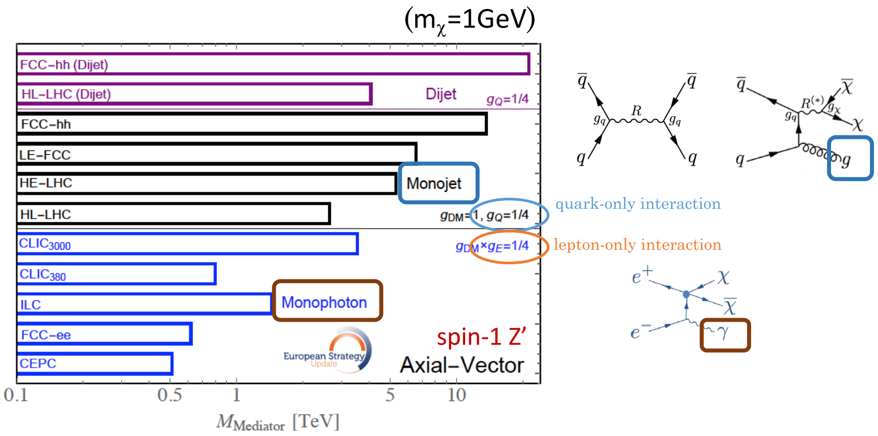




Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

Searching for dark matter with colliders

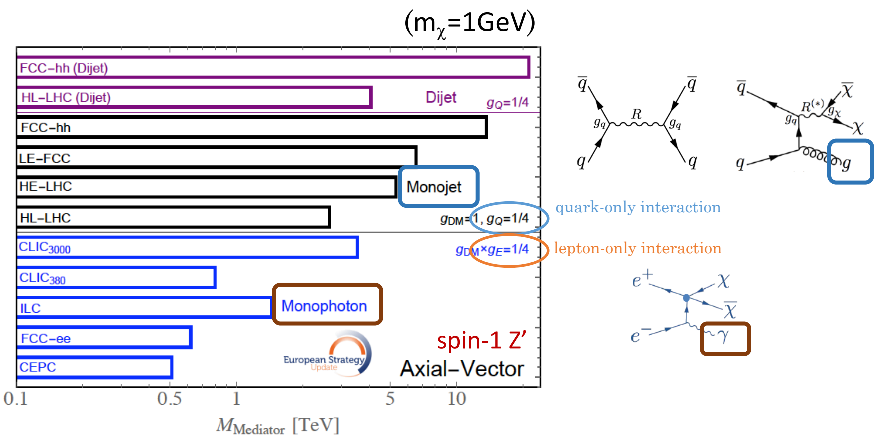
Thermal WIMPs: simplified DM models with one DM particle and one mediator

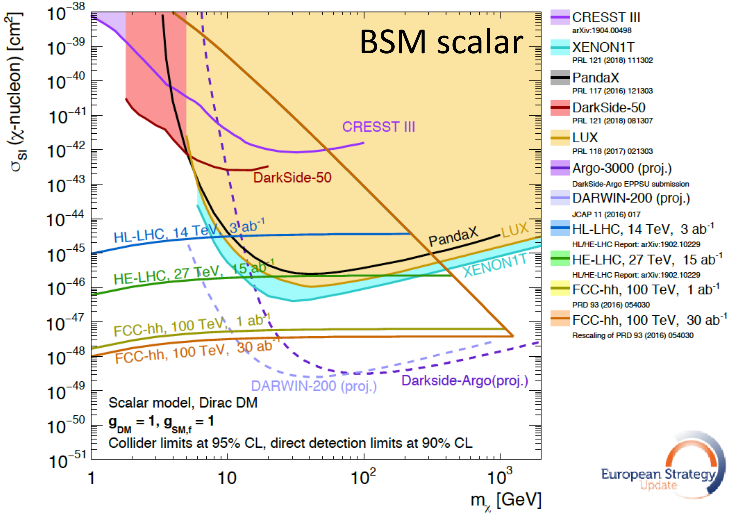


Complementarity:
lepton
and
proton colliders

Searching for dark matter with colliders

Thermal WIMPs: simplified DM models with one DM particle and one mediator

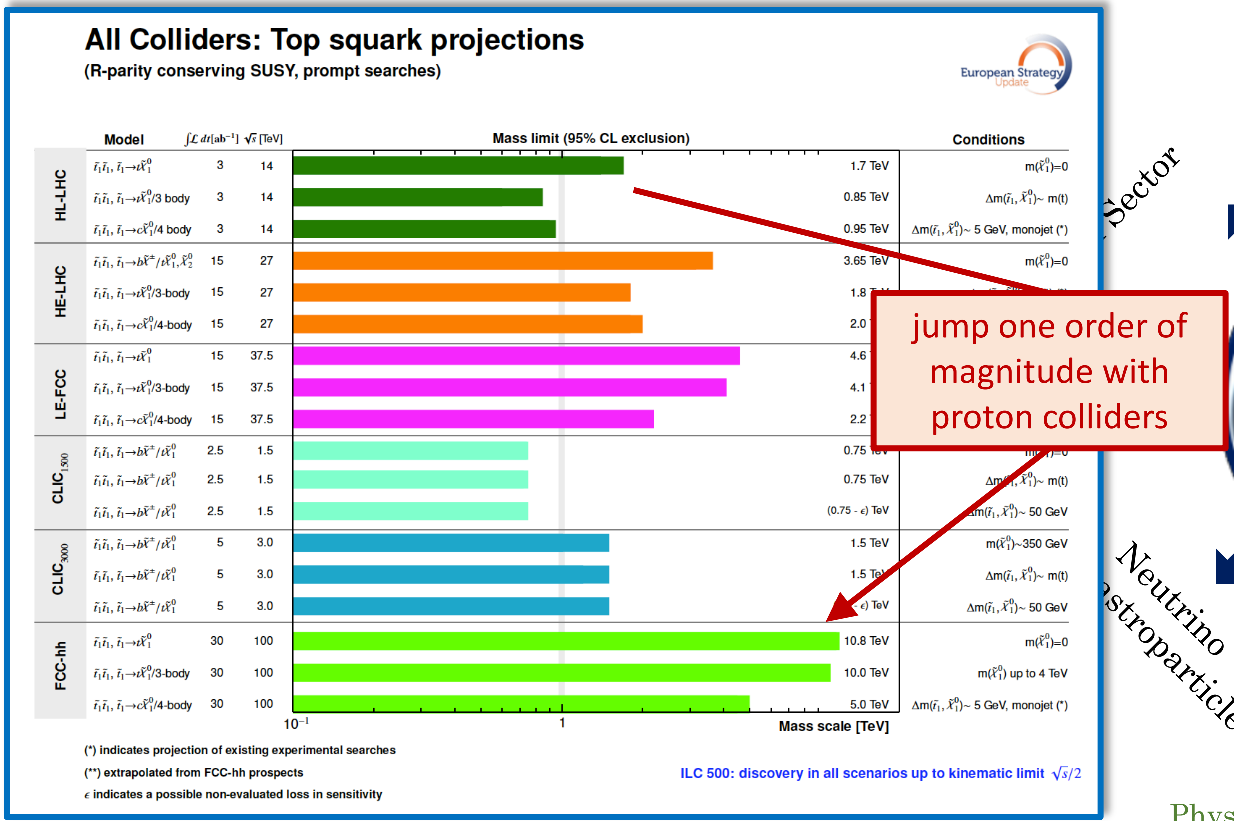


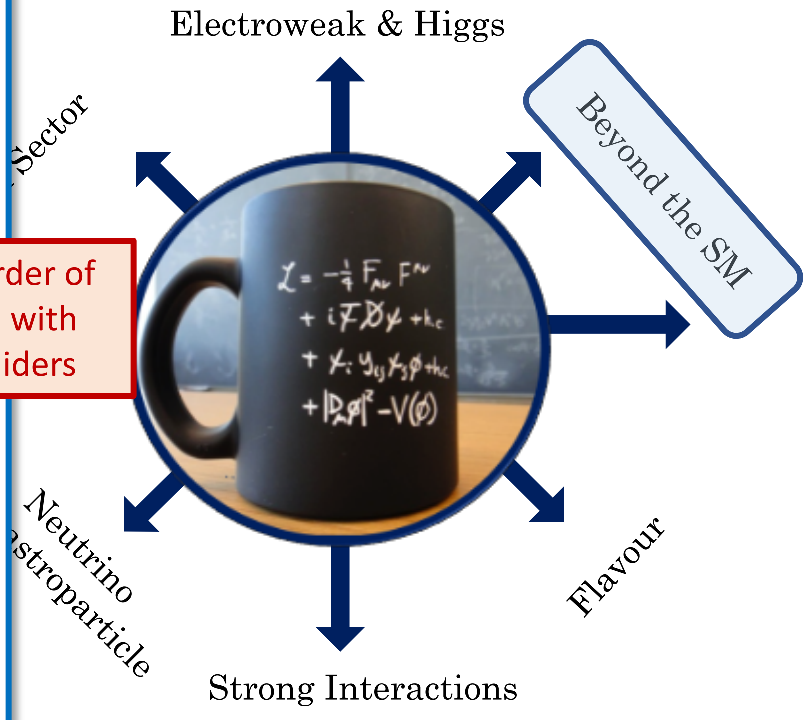


Complementarity:
lepton
and
proton colliders

Maximal overlap with direct & indirect detection sensitivity:
cosmological origin of DM
versus
nature of DM interactions

Addressing the naturalness puzzle with supersymmetry

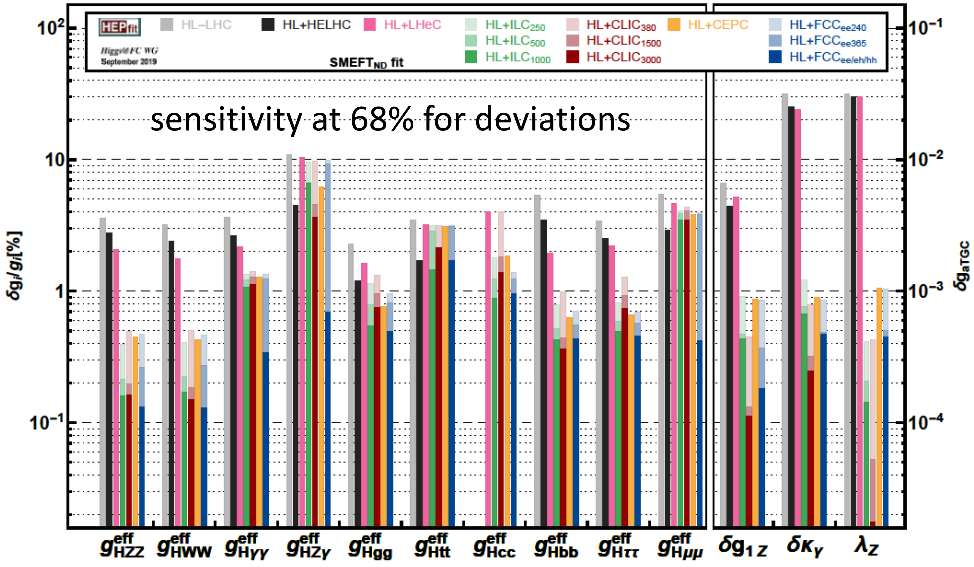




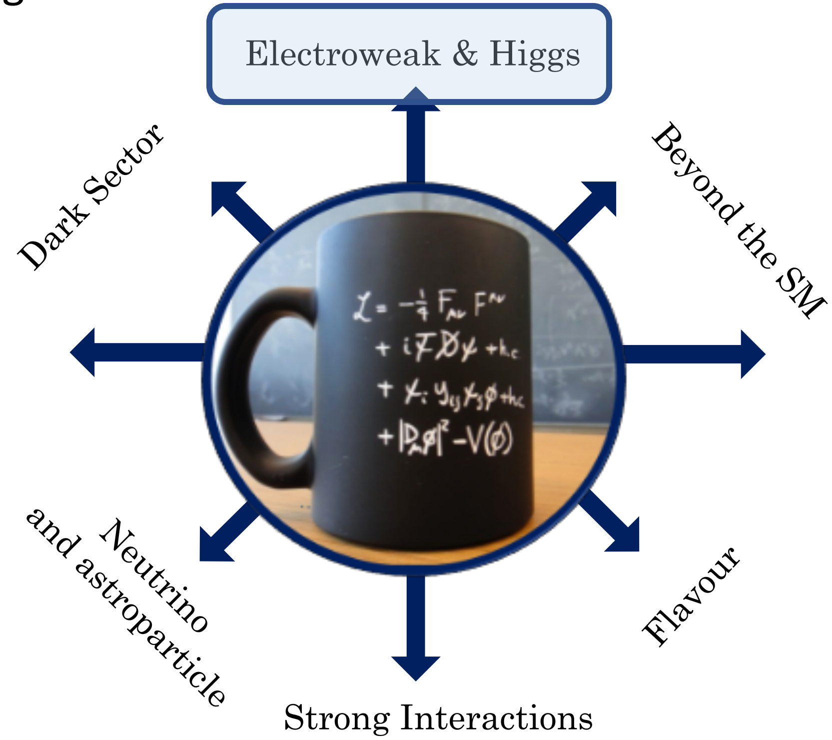
Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

Zooming into the Higgs sector with colliders

Sensitivity for deviations in effective Higgs couplings
(from a global EFT fit – dim-6 SM Effective Field Theory)



Results of the SMEFT fit projected in effective couplings: $g_{HX}^{\text{eff}\,2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\text{SM}}}$



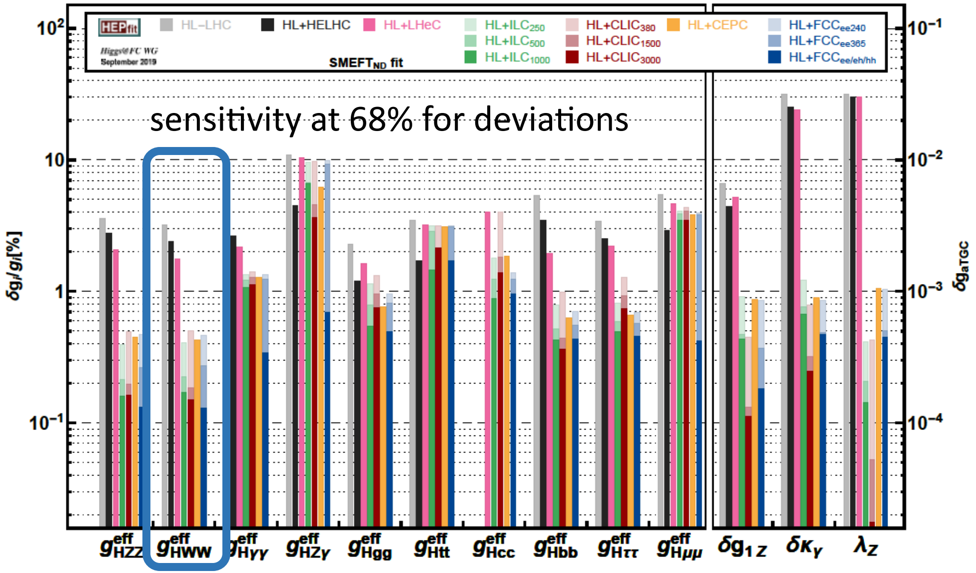
Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

Sensitivity for deviations in effective Higgs couplings

(from a global EFT fit – dim-6 SM Effective Field Theory)



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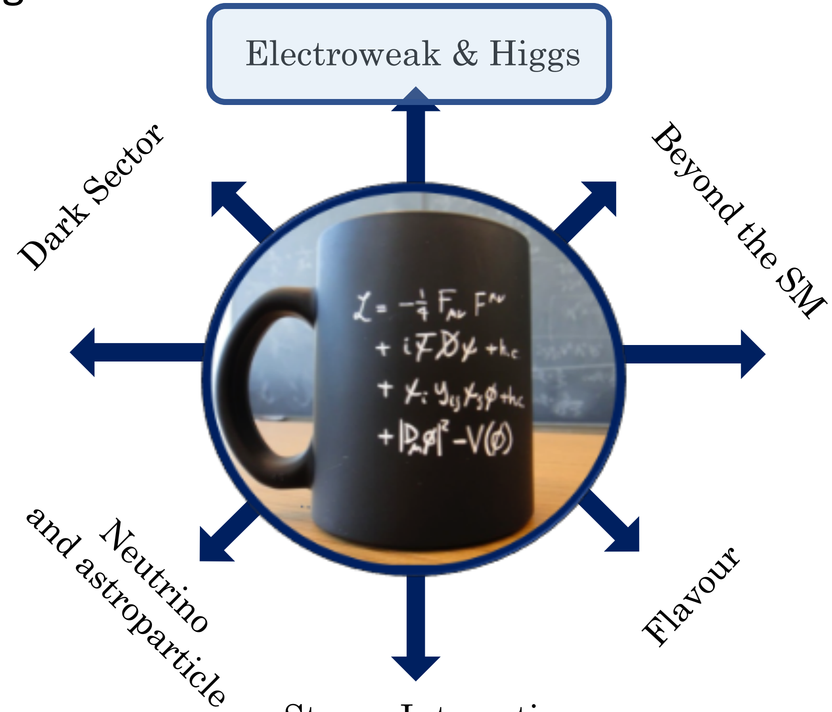

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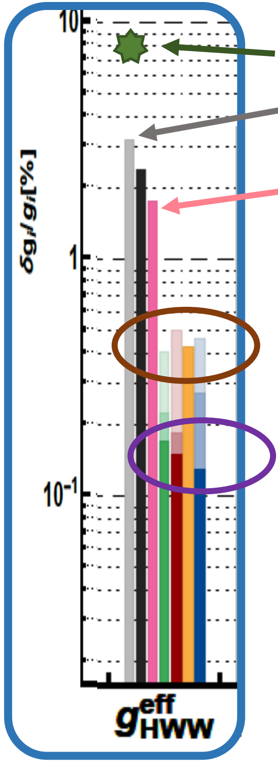

today

HL-LHC expectation (6000fb^{-1})

HL-LHC ⊕ LHeC expectation

HL-LHC ⊕ e^+e^- Higgs Factories (~250 GeV)

HL-LHC ⊕ e^+e^- Higgs Factories (~250 GeV)
⊕ Energy Frontier
(ILC@1TeV, CLIC@3TeV, FCC-pp@100TeV)

The improvement is in the complementarity!

[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

Complementarity between ee/eh/hh colliders – case for the FCC project

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W[%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z[%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g[%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ[%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$[%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c[%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t[%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b[%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ[%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ[%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H[%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

only FCC-ee@240GeV

only FCC-hh

ALL COMBINED

[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

Complementarity between ee/eh/hh colliders – case for the FCC project

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

the coupling we looked at on the previous slide

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ALL COMBINED

only FCC-ee@240GeV

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[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

Complementarity between e^+e^- and proton colliders

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

the coupling we looked at on the previous slide

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+	ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
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adding 365 GeV runs

adding FCC-ep

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

Complementarity between e^+e^- and proton colliders

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

the coupling we looked at on the previous slide

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+[illegible]	[illegible]ee/hh	HL+FCC[illegible]	[illegible]L+FCC-hh	HL+FCC-ee/eh/hh
κ_W[%]	0.86	0.38	0.23	[illegible]	[illegible]	0.39	0.14
κ_Z[%]	0.15	0.14	[illegible]	[illegible]	[illegible]	0.63	0.12
κ_g[%]	1.1	0.88	[illegible]	[illegible]	[illegible]	0.74	0.46
κ_γ[%]	1.3	[illegible]	[illegible]	[illegible]	[illegible]	0.56	0.28
$\kappa_{Z\gamma}$[%]	10.	[illegible]	[illegible]	[illegible]	[illegible]	.89	0.68
κ_c[%]	1.5	[illegible]	[illegible]	[illegible]	[illegible]	–	0.94
κ_t[%]	3.1	3[illegible]	[illegible]	[illegible]	[illegible]	0.99	0.95
κ_b[%]	0.94	0.[illegible]	[illegible]	[illegible]	0.52	0.99	0.41
κ_μ[%]	4.	3.[illegible]	[illegible]	0.41	0.45	0.68	0.41
κ_τ[%]	0.9	0.6[illegible]	0.39	0.49	0.63	0.9	0.42
Γ_H[%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

complementarity between
e^+e^- Higgs Factories
and
high-energy proton colliders

only FCC-ee@240GeV

adding 365 GeV runs

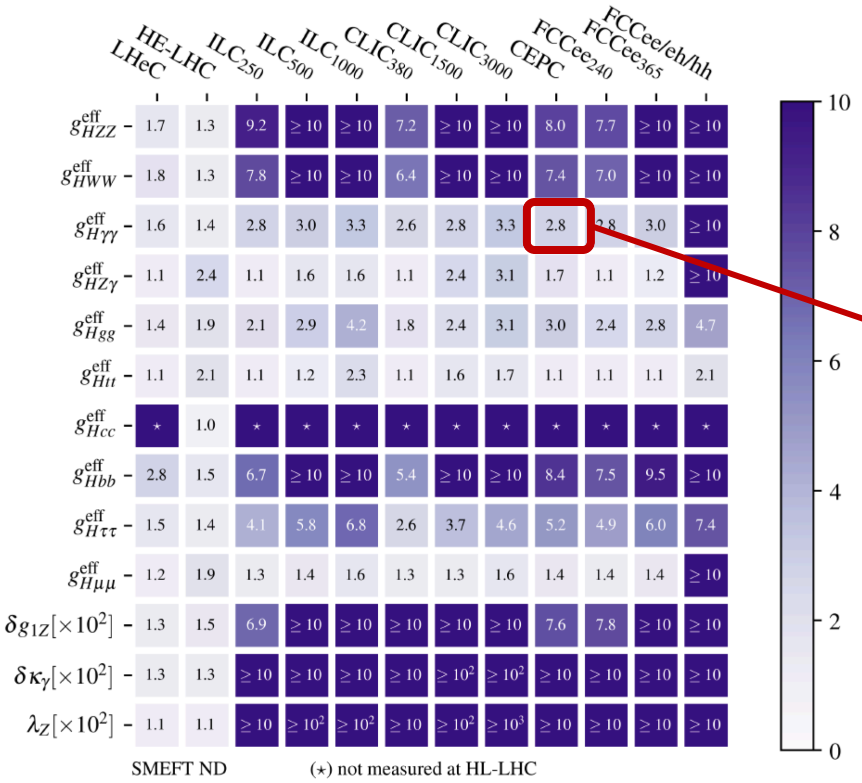
adding FCC-ep

only FCC-hh

ALL COMBINED

[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

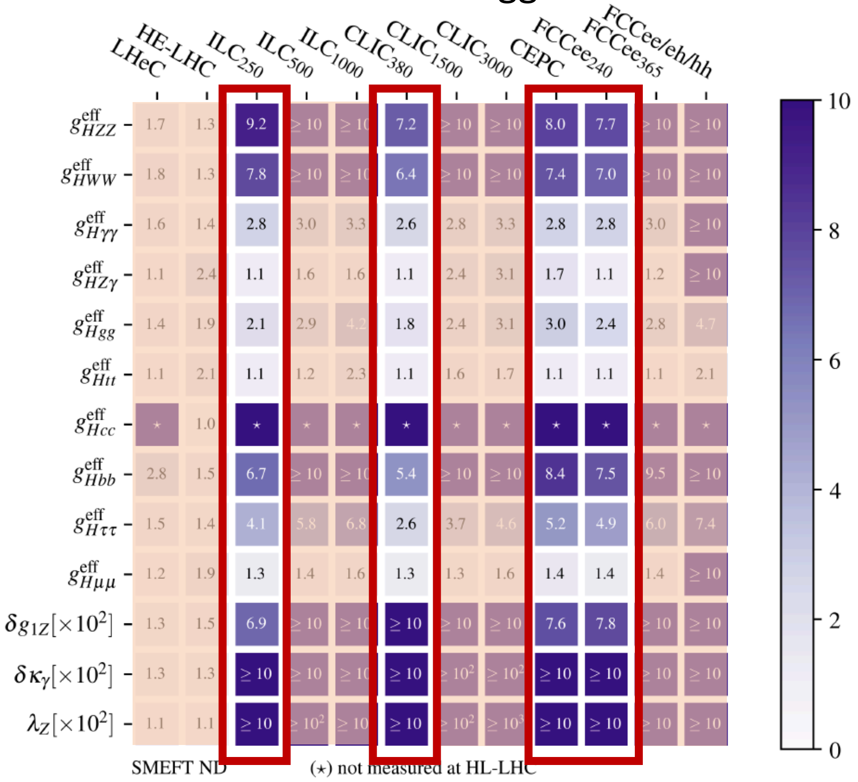


improvement factor adding CEPC results additional to HL-LHC results

[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

Comparable improvement from
HL-LHC to e^+e^- Higgs Factories



[J. de Blas et al., JHEP 01 (2020) 139]

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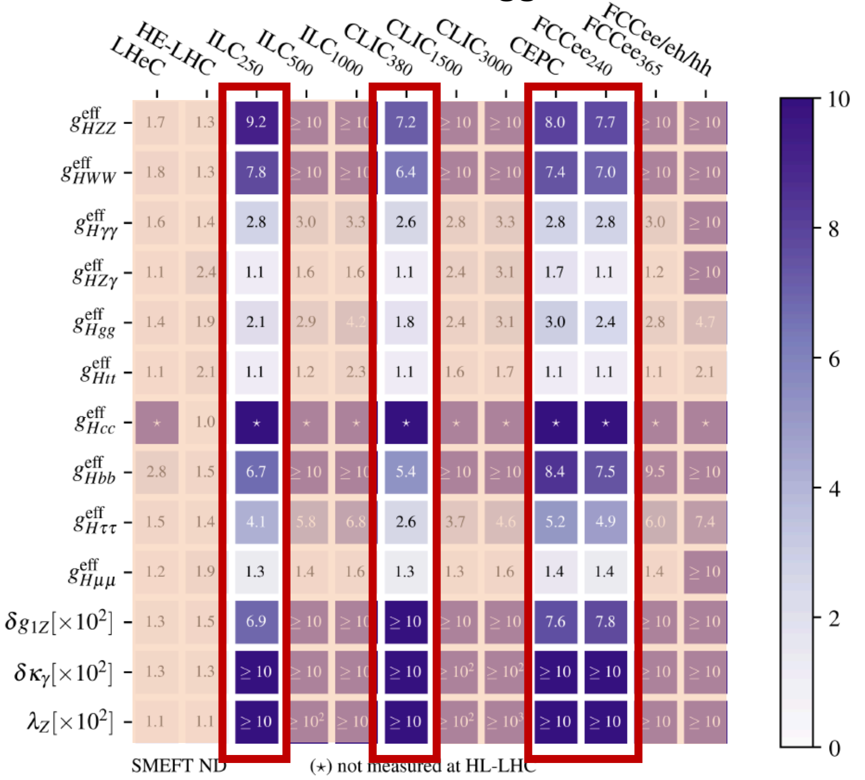


Results from a global EFT fit for FCC-hh with any of the four e^+e^- Higgs Factories proposed

$SMEFT_{ND}$	HL+ILC_{250}+FCC-hh	HL+$CLIC_{380}$+FCC-hh	HL+CEPC+FCC-hh	HL+$FCC\text{-}ee_{365}$+FCC-hh
$g^{eff}_{HZZ}[\%]$	0.35	0.46	0.38	0.21
$g^{eff}_{HWW}[\%]$	0.36	0.46	0.36	0.21
$g^{eff}_{H\gamma\gamma}[\%]$	0.47	0.55	0.48	0.38
$g^{eff}_{HZ\gamma}[\%]$	0.78	0.83	0.76	0.72
$g^{eff}_{Hgg}[\%]$	0.73	0.88	0.54	0.56
$g_{Htt}[\%]$	3.1	2.2	3.1	1.7
$g_{Hcc}[\%]$	1.8	3.9	1.8	1.2
$g_{Hbb}[\%]$	0.75	0.95	0.58	0.51
$g_{H\tau\tau}[\%]$	0.78	1.2	0.61	0.54
$g_{H\mu\mu}[\%]$	0.54	0.61	0.53	0.46
$\delta g_{1Z}[\times 10^2]$	0.078	0.04	0.08	0.028
$\delta \kappa_{\gamma}[\times 10^2]$	0.12	0.079	0.089	0.048
$\lambda_Z[\times 10^2]$	0.042	0.043	0.1	0.047

the coupling we looked at on the previous slides

Differences at e^+e^- colliders:

model independent total width Γ_H measured at circular (1.1%@FCC-ee) and linear (2.2%@ILC250)

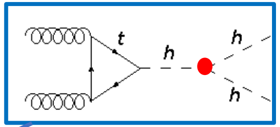
the combination of 250 GeV and >250 GeV e^+e^- data is relevant

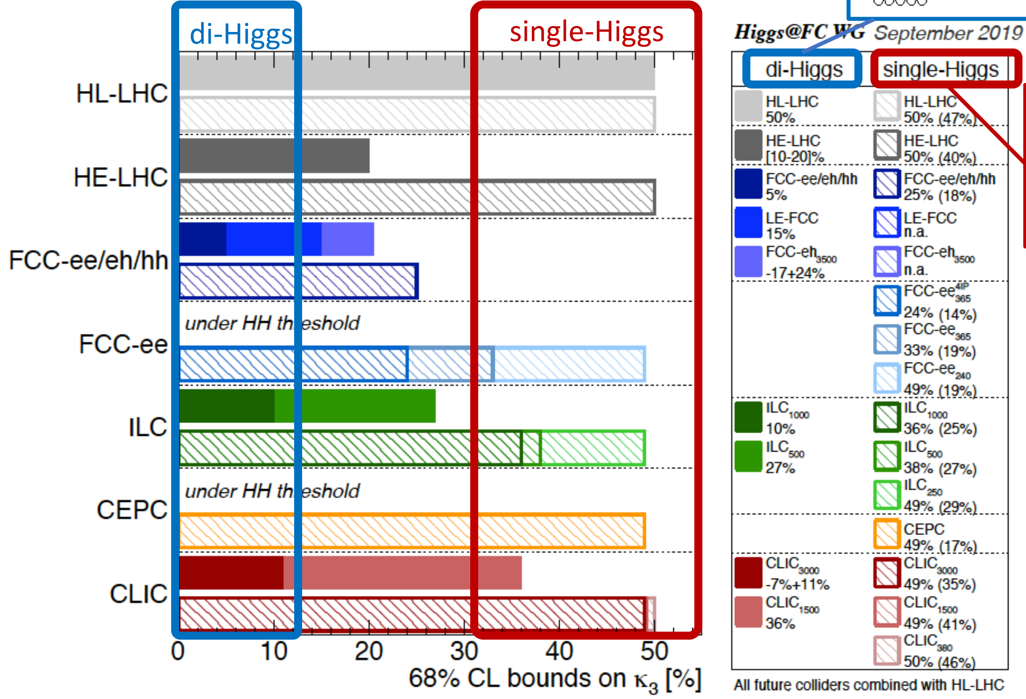
ILC @ 250+500 GeV would reach 1.1%

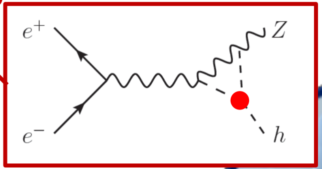
[J. de Blas et al., JHEP 01 (2020) 139]

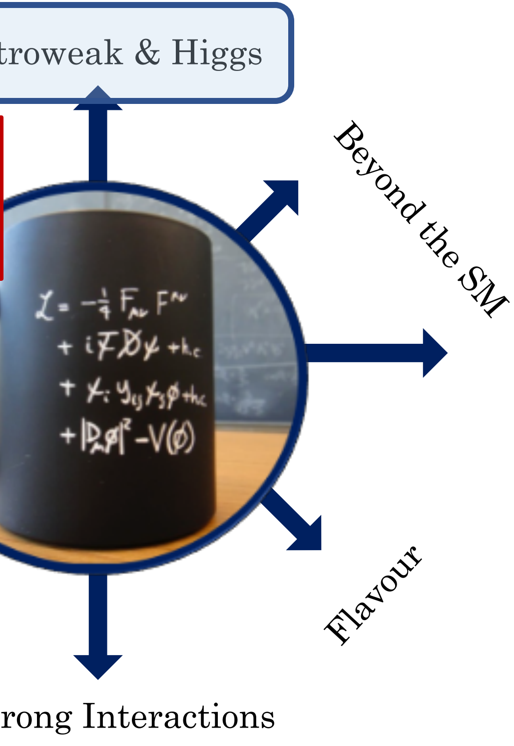
Zooming into the Higgs sector with colliders

The Higgs boson cubic self-coupling (κ_3)









Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

[J. de Blas et al., JHEP 01 (2020) 139]

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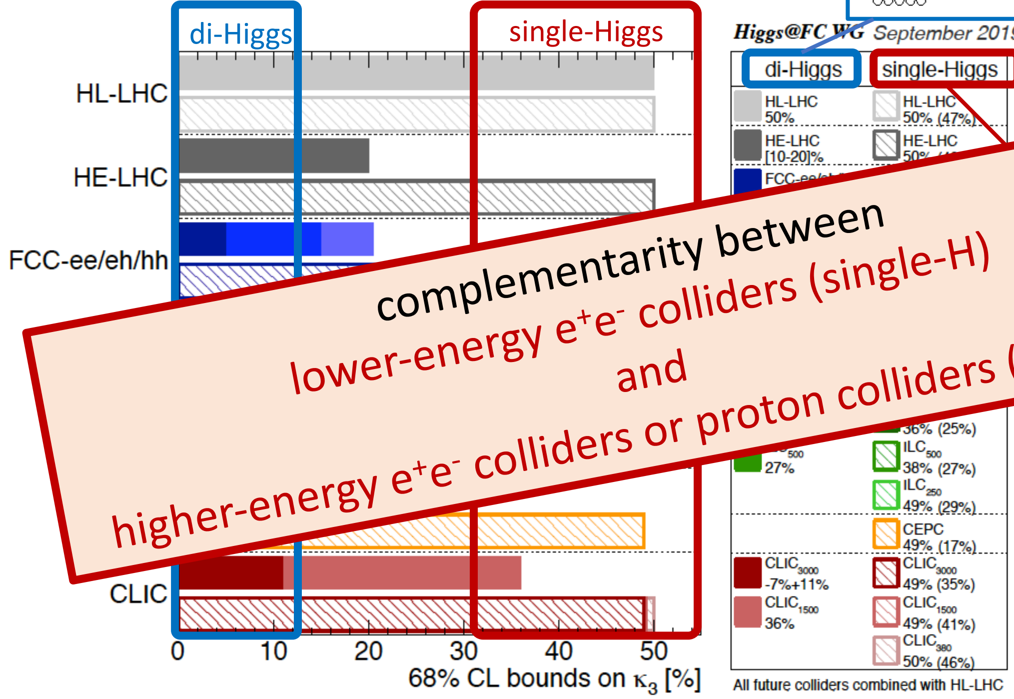
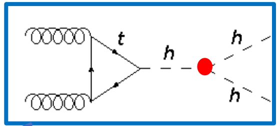
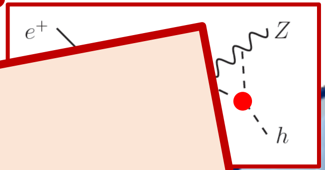
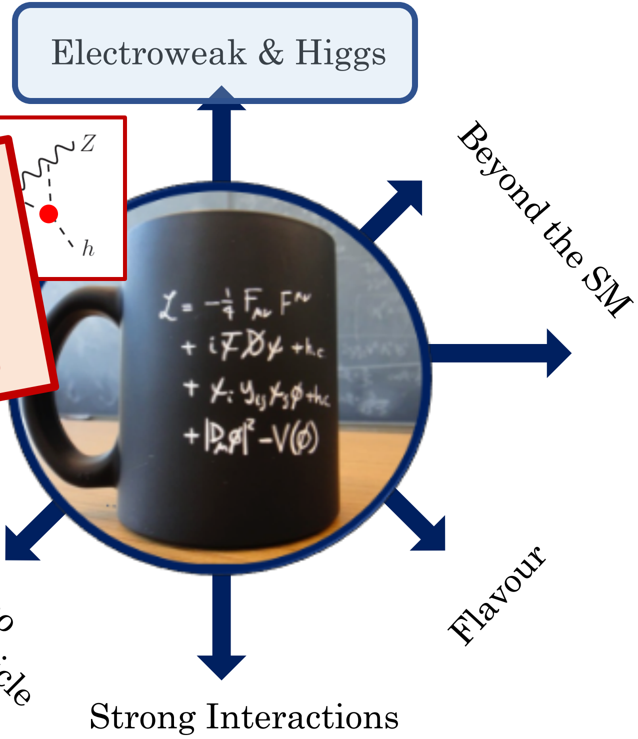






complementarity between
lower-energy e^+e^- colliders (single-H)
and
higher-energy e^+e^- colliders or proton colliders (double-H)



Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

[J. de Blas et al., JHEP 01 (2020) 139]

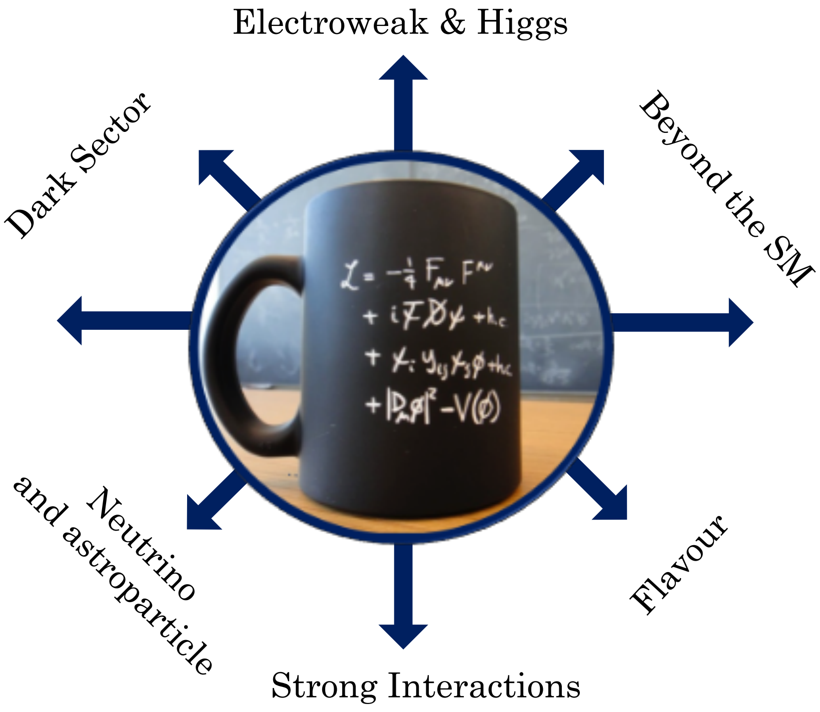
Principle collider avenues to seek new phenomena

High-energy colliders have a unique capability to address the most profound open questions in particle physics

Although with novel theoretical reasoning we are given several avenues where we <u>could</u> find new physics, we do not know where we <u>will</u> find new physics

> This provides an argument, in a global context, for an inclusive collider programme exploiting complementary ee/eh/hh future colliders aiming for broad coverage

… strategy, next presentation …



Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

The bold and the beautiful of colliders

- With the HL-LHC and SuperKEKB the immediate future for particle physics colliders looks bright, and provides ample opportunities for innovative experimental and theoretical research to unlock physics that was initially thought to be out of reach at these colliders
- Clearly motivated by physics arguments, e^+e^- Higgs Factories are technically ready to become operational in our medium-term future and with the ambition to integrate the concepts of B/c/τ, EW and top quark Factories in their research programs
- Because of the complementary to address the open questions in particle physics, there is a motivation for a new energy frontier machine, potentially at a later stage, to unlock the physics potential of 100 TeV proton collisions

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In my view, we have a few years in front of us to join forces on a global scale
to organize together our concrete ambition for the colliders of the 21st century
… and if we do this together, it better be with a bold moonshot ambition

Thank you for your attention!

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